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Soil liquefaction mitigation in geotechnical engineering: An overview of recently developed methods

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ABSTRACT

Triggered liquefaction in earthquakes, that soil displays fluid-like characteristics caused by an on-going increase of pore water pressure and reduction of the effective stress, can damage existing building foundations and other structures and result in significant economic losses. Many previous studies have investigated methods, which effectively control sand liquefaction while minimizing cost, environmental impact and other related disturbances. Recently, the rapid development of materials technology and multidisciplinary approaches has made available new materials suitable for improving the liquefaction resistance and enabling other liquefaction mitigation techniques. To raise some important questions and encourage further research and discussions, investigations on the recently developed liquefaction mitigation methods are reviewed in this study. The review first analyzed and discussed the characteristics of the newly developed methods including the mitigating mechanism, effectiveness, and possible executive problems for purpose of building sufficient understanding into the progress of liquefaction resistance. Then, the applicability and uniformity in the soil with different pore size, possible disturbance to nearby structures are discussed. Additionally, the potential cost and duration time of the mitigation measures for site constructions are briefly described. Through this review, some important questions and discussions are raised; the readers will fully understand the research trend of liquefaction mitigation and further explore new methods and techniques that could be effective, easy for on-site construction, low cost, environment-friendly and highly durable. This study recommends long-term in-situ investigation on mitigation effectiveness, duration time and quantitative cost assessment.

1. Introduction

Liquefaction induced by static or dynamic loading in saturated sandy soil can cause significant damage to building foundations and existing structures, such that the sudden instability may result in the destruction of structures, economic losses and even loss of human life [1–3]. Liquefaction problems have been reported frequently after earthquakes, such as the earthquakes that occurred in 1964 Niigata, Japan, 1976 Tangshan, China, 1999 Kocaeli, Turkey, 2008 Wenchuan, China, and 2011 the Tohoku Region Pacific Coast Earthquake, Japan. This has motivated increasing research into improving liquefaction resistance and other liquefaction mitigation methods.

The main cause of liquefaction is the loss of shear strength due to an increase in pore water pressure and a reduction of the effective stress of soil, which eventually leads to the phenomenon where sandy soil displays fluid-like characteristics [4,5]. Soil improvement methods are most commonly employed to reduce or eliminate the effects of liquefaction. Research on the physical properties of liquefiable sand shows that the density of sand [6], content of fines [7,8], coefficient of uniformity [9] and other factors [10–12] has a great influence on liquefaction. However, control of these factors was not the best way to improve liquefaction resistance.

Earlier studies have shown that the addition of metal strips and bars, existing plant roots and soil densification can improve liquefaction resistance [13–15]. However, the use of metal strips present problems including reduced ductility and uncertainty of the influence of environmental factors. Additionally, the durability of liquefaction alleviation is poor when utilizing plant roots. Soil densification through dynamic compaction is energy intensive. Moreover, this method has a great impact on the surrounding infrastructures, and the depth of compaction is limited. Therefore, researchers continue to explore new mitigation methods to prevent the occurrence of liquefaction.

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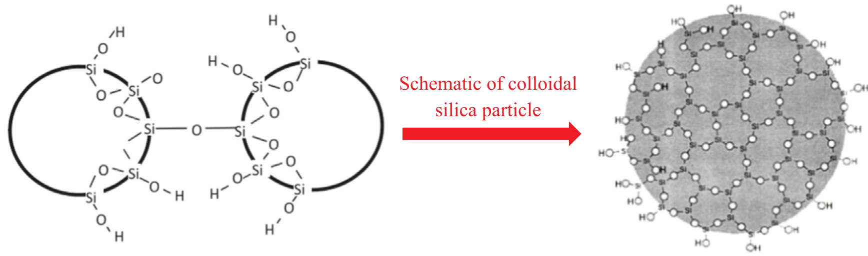

Fig. 1. Formation of siloxane bonds as a colloidal silica particle gel [21,23].

Existing methods for improving liquefaction resistance include grouting with cement or chemical solutions (sodium silicate, acrylate, epoxy, etc.), foundation densification, gravel columns, foundation replacement and dewatering. While most of these techniques have advanced over the years, their application is problematic because of high construction cost, impact to surrounding infrastructure or effects on the surrounding environment. For example, traditional cement and chemical grouting, though widely used, pollute the surrounding environment and waterways, and risk damaging adjacent buildings when handled improperly. Thus, new techniques and methods for liquefaction mitigation for large-area construction should be developed that are low cost and non-damaging to existing structures while at the same time being environment-friendly, sustainably developed and pollution-free [16].

Lately, new liquefaction mitigation methods are constantly emerging due to the rapid development of science, technology and multidisciplinary engineering approaches. New concepts like passive site remediation, microbial geotechnology and induced partial saturation have been proposed. Meanwhile, new methods of liquefaction mitigation have been developed based on these concepts, such as nanomaterial suspension grouting, biocementation, air injection, biogas and liquefaction mitigation using other geomaterials [17]. In particular, it is the availability of new materials and techniques that has promoted the development of liquefaction mitigation technologies.

To sufficiently understand the progress of liquefaction resistance in present literature, investigation into recently developed liquefaction mitigation methods were reviewed in this paper with a focus on soil improvement with new concepts and materials. First, the mitigating mechanism, characteristic, effectiveness, possible executive problems in engineering practice were analyzed and discussed in detail. Then, the applicability and uniformity in soils with different pore sizes and any possible disturbance to nearby structures were presented. Further, the duration time and potential cost of the mitigation measures for site construction were simply discussed based on laboratory tests' results. It was recommended that long term in-situ testing should be performed to investigate mitigation effectiveness and duration time. This review does not attempt to discuss all available soil improvement techniques and points; instead, it will raise some important questions and encourage further research and discussion. Many of the recently developed techniques the paper presents are still in the stage of laboratory investigation and not used in the engineering practice for mitigation of seismic-hazard, thus, not all the points, e.g. duration time, exact cost assessment for on-site practice, can be sufficiently addressed. However, based on the presented research trend of liquefaction mitigation in this study, researchers can fully understand the relationship between the development of science, technology, new materials and multidisciplinary engineering approaches, and encourage further explore of new methods and techniques, which could be effective, easy for on-site construction, low cost, environment-friendly and highly durable.

2. Recently developed methods

2.1. Nanomaterials

With the development of new technology and multidisciplinary engineering approaches, the use of nanomaterials has shown superior performance in geotechnical engineering. This is due to the nano-scale particle size, which could penetrate finer soils without the use of high-pressure infusion, greatly reducing the disturbance effect on surrounding environments compared with traditional materials [18]. For liquefaction mitigation, the nanomaterials investigated mostly are colloidal silica (CS), bentonite and laponite. These nanomaterials are non-toxic to soil and groundwater. Hence, this section mainly describes the application of these three kinds of nanomaterials in the application of liquefaction mitigation, including mitigation effects, mechanism and potential problems.

2.1.1. Colloidal silica

Colloidal silica (CS) is an aqueous suspension of silica nanoparticles produced from saturated solutions of silica acid [19]. The particle size is generally between 2 and 100 nm. During manufacturing, CS solutions are stabilized against gelation with alkali solutions. Alkaline solutions ionize the nanoparticles so that they repel each other [20]. Gelation that relies on the interaction between particles is induced by weakening these repulsive forces, resulting in the formation of a coherent network of siloxane (Si—O—Si) bonds (Fig. 1) that bind the soil particles together and restrain the pore fluid [21]. The main factors that influence the transferal of colloidal silica in liquefiable sand are the viscosity of the colloidal silica stabilizer, hydraulic gradient and the hydraulic conductivity of the liquefiable soil. Additionally, the time of formation of the gel is mainly affected by the percentage of silica in the solution, the size of the silica particles, pH value, ionic strength and the temperature of the solution [22].

From experimental studies, it was found that CS has the advantages of low initial viscosity, controllable gel times, good long-term mechanical stability and minimal disruption to infrastructure due to the small particle size and surface charge of the silica particles. Electrical inter-particle forces dictate the behavior and fabric formation of the particles, and chemical bonding continues after the initial resonating gel state was reached. Hence, continuing bonding causes an increase in the strength of the gel over time. Moreover, CS was nontoxic, biologically and chemically inert, and has excellent durability characteristics. Therefore, based on these advantages, CS particles gel in low concentrations can effectively alleviate liquefaction of sand by cementing individual grains together and fixing the pore fluid [20,22–25]. Experiments from Persoff et al. [26] showed that the strength of the treated sand increased with an increasing concentration of CS. The shear strength would continue to increase as the time of gel increases as well. Furthermore, the unconfined compressive strength of the CS treated sand was proportional to the concentration of CS particles, up to a maximum of approximately 400 kPa. Although using CS was found to be an effective method to enhance sand strength, the permeability of the treated sand decreased with increasing CS concentration in a nearly log-linear manner down to a minimum of 2×10^{-9} cm/s (Fig. 2). This

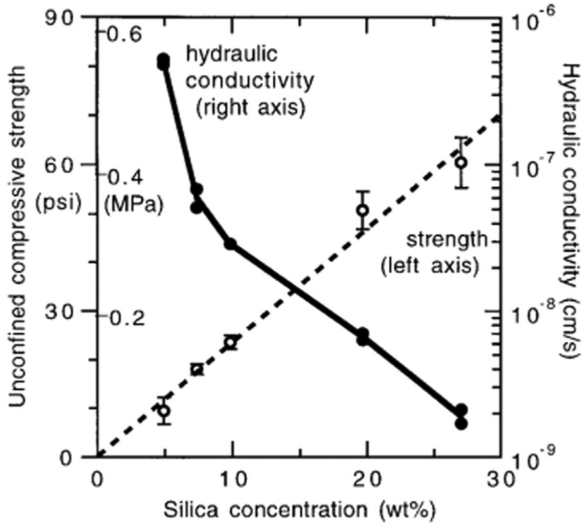

Fig. 2. Compressive strength and hydraulic conductivity of samples of Monterey sand grouted with various dilutions of Ludox SM [26].

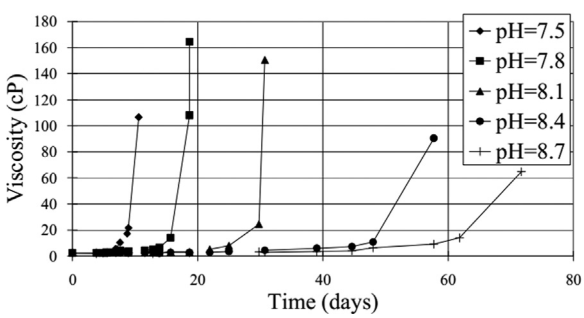

Fig. 3. Typical colloidal silica gel time curves for 5 wt% solutions at an ionic strength of 0.1 N [27].

indicates that CS could not reach the designed destination in a large area site with uniform distribution. In order to effectively and adequately transfer CS in practical applications, Gallagher and Lin [27] found that the CS gelation rate could be delayed to control the gel time, so that CS could effectively and uniformly penetrate liquefiable sand when the CS content was 5 wt% with the pH value between 7.5 and 8.7 (Fig. 3). The experimental results showed that the uniformly distributed sample provided sufficient strength to improve liquefaction resistance.

However, it is difficult to prevent CS sinking before it reaches the designed location because the density of CS was slightly higher than water. Hamderi and Gallagher [20] used a pilot-scale model combined with 3D fluid simulations to predict the injection rates (ranging from 65 to 9000 ml/min/well) required for adequate stable delivery. The experiment results indicated that CS, in as little as 1% by weight, could effectively mitigate the liquefaction risk in loose sands by cementing individual grains together without reducing the concentration beyond the lower limit of 1% in the pore fluid. Meanwhile, increasing the injection rate could provide sufficient horizontal pressure (Fig. 4) to adequately deliver an appropriate concentration of dilute CS for liquefaction mitigation. Conversely, to achieve penetration to the desired depth vertically, the CS injection rate should be slow [28,29]. Conlee et al. [21] used the centrifuge model test and Spencer et al. [23] used the resonant column test to study the effects of different content of CS. Their results indicated that ground deformations of lateral spreading and settlement were progressively reduced with increasing content of CS treated sand and that after CS treatment, the soil presented greater cyclic resistance ratios and lower cyclic shear strains. The shear modulus increased with an increasing content of CS, and change in the damping ratio was not significant. Furthermore, Gallagher and Mitchell [24] carried out cyclic triaxial tests and found that once the liquefaction of untreated sand was triggered, large strains occurred rapidly, and the samples collapsed within a few additional loading cycles. However, the treated soil with CS at concentrations of either 5, 10, 15, or 20% could bear more cycles with very little strain during cycle loading (Fig. 5). With the relative density increasing, the number of cycles for initial liquefaction also increased. They also found that the effect of 20% CS on the cyclic strength of loose sands was approximately equivalent to dense sands with the relative density of 80% (Fig. 6). The results of development curves of pore pressure clearly demonstrated a beneficial increase of the cyclic strength of loose sand by CS treatment (Fig. 7) [25].

2.1.2. Bentonite

Bentonite is an aluminum phyllosilicate, and a clay consisting majority of montmorillonite. Due to the thixotropic properties of bentonite dispersions in water, it is highly effective when used to enhance the performance of loose sands as pore fluids. Bentonite is easy to obtain, low cost, and environment-friendly. The rheological properties of bentonite are mainly affected by clay concentration, pH, water ionic strength, type of cation and anion. So when these factors change, the bentonite dispersions will appear in different "states", i.e. sol (a sol state is characterized by the presence of clusters with a finite lifetime and may consequently be inhomogeneous, which crucially differs from a homogeneous liquid state), repulsive gel, attractive gel and sediment [30]. Bentonite can effectively enhance the sand liquefaction resistance. This is because bentonite has the rheological properties of pore fluid and the formation of a bentonite gel with soil-like properties in the pore space could restrain the motion of sand grains under the action of earthquakes (Fig. 8) [31]. Due to the fact that bentonite dispersion has a high initial yield stress and viscosity, and the time of gelation is very short, it will affect the permeability coefficient of sand. This results in a reduced performance for large areas and non-uniform transmission in liquefiable sand [32]. For these reasons, Santagata et al. [33] studied the rheological properties of bentonite with sodium pyrophosphate (SPP) ranging from 0% to 2% by mass of bentonite. The results showed that the application of SPP could significantly improve the rheological properties of bentonite suspensions (Fig. 9) [34]. For dispersions with SPP content greater than 5%, bentonite could penetrate the sand more effectively, and the penetration pressure of the bentonite suspensions not only improved the cohesion and friction angle of the clean sand, but could further enhance the ability to resist liquefaction over time [34,35].

Undrained static triaxial, dynamic triaxial and resonant column tests were carried out to study the effect of different contents and aging time on liquefiable sand [35–37]. The results showed that samples treated with bentonite exhibited 10 times increase of the number of cycles required for liquefaction compared to the untreated sand for the same skeleton relative density and cyclic stress ratio (CSR). As discussed above, bentonite has the rheological properties and soil-like properties when formed a gel, this means that using bentonite can increase the soil elastic behavior, delay the generation of excess pore pressure in cycles of loading (Fig. 10) and restrain the motions of the sand grains under earthquakes.

The storage modulus (E′), is used as a measure of the stored energy and represents the elastic portion. E′ is related to the ability of a material to return energy. Thus, the value of E′ is a measure of how elastic a material is and ideally is equivalent to Young's modulus (Es), which expresses the ability of the material to store elastic deformation energy. The storage modulus characterizes the index of resilience after deformation of the material. E′ can be calculated in specific conditions, e.g. for the linear elastic material: $E' = E_s = 3K(1-2\mu)$, where, E_s is Young's modulus, μ is Poisson ratio, K is Bulk Modulus or modulus of volume elasticity. The detailed calculation in other conditions can be found in the references [33,38,39].

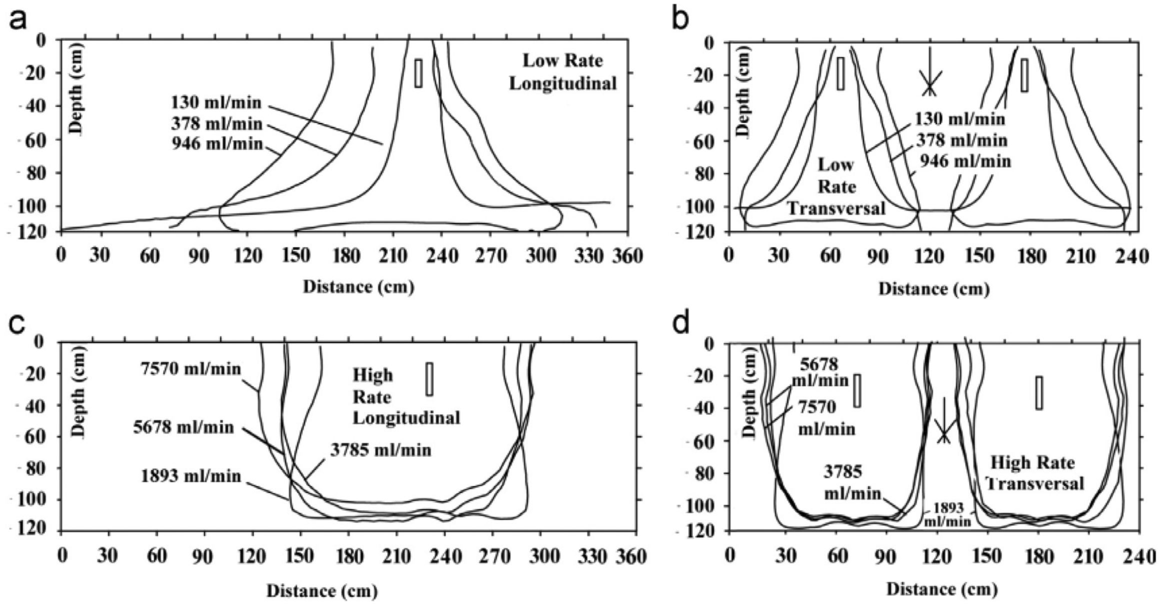

Fig. 4. Advancement of grout plume at different injection rates in a UTCHEM simulation—(a) and (b) on a longitudinal plane passing through one of the two injection wells, and (c) and (d) on a transversal plane passing through both injection wells. Each line shows the front edge of the CS grout for various injection rates in ml/min immediately after half the pore volume of grout was injected [20].

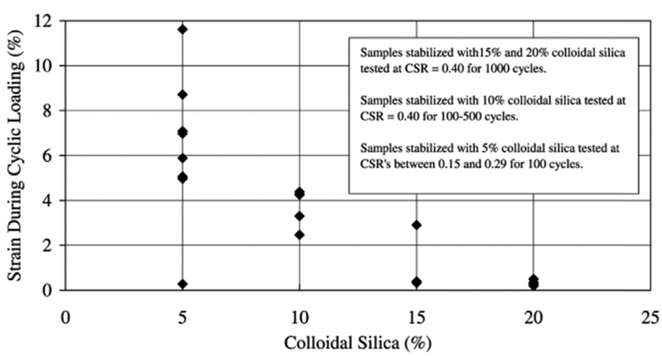

Fig. 5. Percent colloidal silica versus strain during cyclic loading at CSR = 0.4 (CSR = $\frac{\Delta\sigma_C}{2\sigma_3}$, where $\Delta\sigma_C$ is cyclic deviator stress; σ_3 is the initial effective consolidation stress) [24].

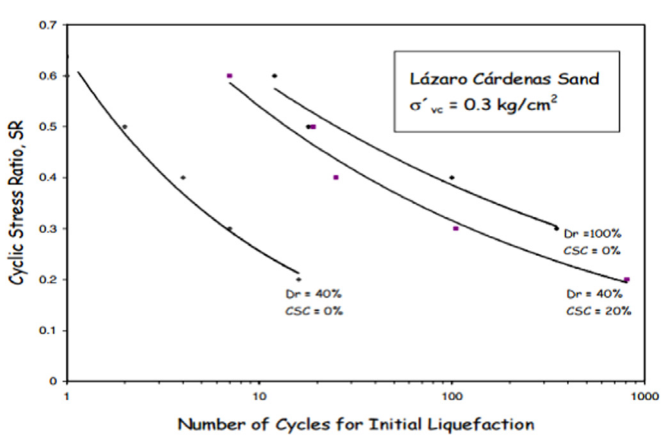

Fig. 6. Effect of density for liquefaction resistance for treated sand with colloidal silica [25].

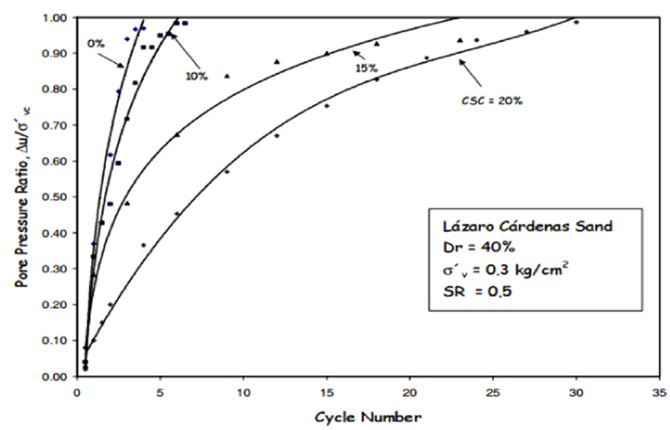

Fig. 7. Effect of colloidal silica content (CSC) on the pressure ratio of pore water [25].

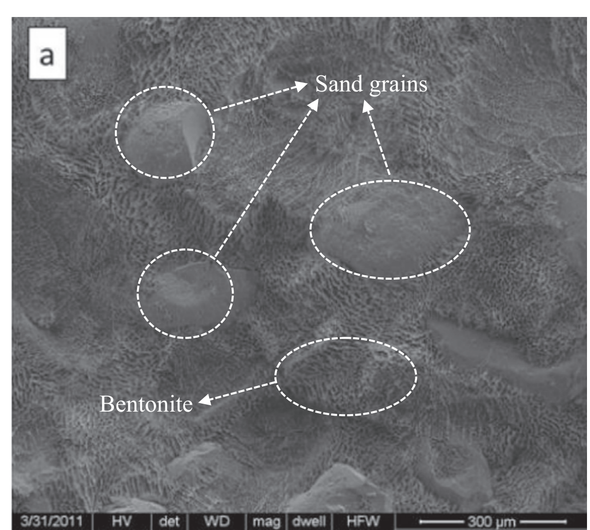

Fig. 8. Cryo-SEM photographs of sand-bentonite [31].

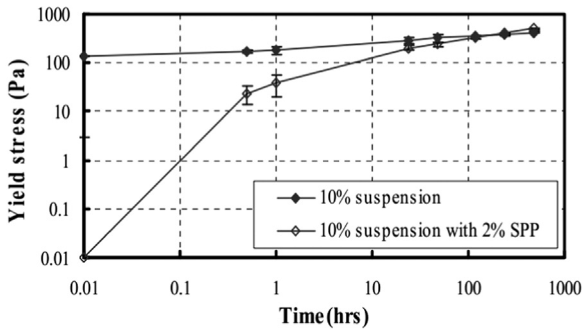

Fig. 9. Thixotropy of a 10% suspension (closed symbols) and a 10% suspension with 2% SPP (open symbols) [34].

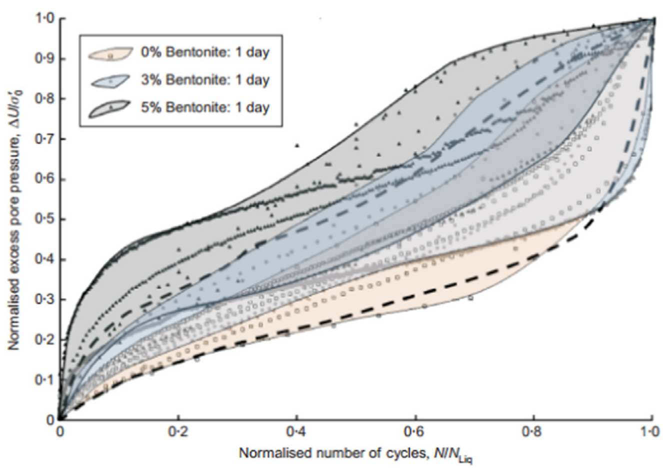

Fig. 10. Normalized mean excess pore pressure against normalized number of cycles to liquefaction for clean sand and sand–bentonite specimens. Dashed lines represent the range for clean sand from the literature (σ_0': effective confining stress at end of consolidation. ΔU: Excess pore pressure.$\sigma_0'/\Delta U$: normalized excess pore pressure. N: number of loading cycles. N_{Liq}: number of cycles to reach liquefaction. N/ N_{Liq}: number of loading cycles normalized by number of cycles to reach liquefaction) [35].

However, the real modulus is of more complicated nature in case of nonlinear and anisotropic properties of materials. It is difficulty to give a unified relation or function to calculate E′ for several reasons: (i) E_s that is the slope of a line is normally calculated over a range of stresses and strains, whereas E′ is derived from what can be considered a point on that line. (ii) The tests used to measure these values are very different. For example, in the stress-strain test, one material is constantly stretched, whereas it is oscillated in the dynamic test. (iii) For a viscoelastic material, E′ is certainly different from E_s. The storage modulus (E′) and the loss modulus (E″) can be calculated through a function, however, E′ is difficult to be defined as a unified function because of the complex influence factors e.g. material type, temperature, time, loading conditions [33,40].

Here, storage modulus is used to describe the elastic (solid) components of the response and to characterize the visco-elastic behavior of dispersions [33]. The storage modulus significantly increases with time because of the thixotropic nature of the bentonite suspension. The number of cycles until liquefaction of sand increases with increasing bentonite content and the cyclic stress ratio become larger until the liquefaction phenomenon does not occur for high bentonite concentration (Fig. 11) [35]. Based on the experimental results of monotonic, cyclic triaxial and resonant column tests on bentonite-sand mixtures, Witthoeft et al. [41] simulated and analyzed the loss of mean effective stress and foundation settlement, respectively. The results also confirmed that the bentonite treated sand could effectively prevent the occurrence of liquefaction.

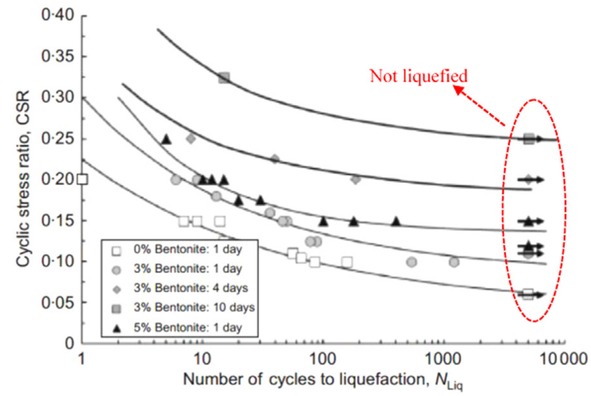

Fig. 11. Cyclic stress ratio against number of cycles with percentage of bentonite and ageing time. (All specimens were prepared at skeleton relative density (D_r) of 35%, 65%. Arrows indicate tests that did not liquefy) [35]

2.1.3. Laponite

Laponite is a synthetic nanoclay that is similar to natural hectorite. Laponite particles are typically 25 nm in diameter and 1 nm in thickness, and are almost one tenth the size of bentonite. Additionally, the plasticity index of Laponite is 1100% greater than bentonite. The advantages of using Laponite for soil treatment include high plasticity, its nontoxic nature, and small size compared with natural clay particles. The main factors that control the structure and the response of the laponite dispersion are concentration, pH and ionic strength [42,43]. Additionally, Mongondry et al. [44] studied the effects of pyrophosphate and polyethylene oxide on the aggregation and gelation of aqueous laponite dispersions. Their results show that the combination between negatively charged surfaces and positively charged edges on laponite particles could be inhibited by adding pyrophosphate and polyethylene oxide, which could delay the gelation of laponite. Therefore, laponite can be evenly distributed in the pores of sand for a short time, because of early Newtonian behavior and a delayed gelation process [42]. In fact, laponite suspensions prepared with deionized water have a cellular microstructure formed by elongated cells of a size several orders of magnitude greater than the natural clay particles, which is consistent with the structure of an attractive gel. With increasing time, the formation of the laponite suspension in the pore space shows solid-like properties. This means that the laponite suspensions not only fill the pores as a pore fluid, but also show solid-like properties to bond the sand particles together (Fig. 12) [43]. Therefore, it can reasonably explain the micro-mechanism of liquefaction mitigation in macroscopic geotechnical properties [45]. Ochoa-Cornejo et al. [42] used cyclic triaxial experiments to explore the effect of small amounts of laponite on liquefiable sand. The experimental results indicate that 1% concentration of laponite was equivalent to samples with content of 3% bentonite (Figs. 13 and 14) [31].

Furthermore, Huang and Wang [43] studied liquefaction mitigation of silty sand treated with laponite using dynamic triaxial tests. They found that the number of cycles to liquefaction and cyclic stress ratio (CSR) under cyclic loading increased with an increase in the concentration of laponite. With the curing time changes, the number of cycles to liquefaction also increased (Fig. 15) [42]. The laponite suspension was initially a Newtonian liquid when the concentration increased up to approximately 3% by mass of water. However, the change with time from sol to a "solid-like" gel can raise the shear strength and increase the shear modulus. For the sand-laponite specimen, when increasing the content of laponite suspension and applying the higher cyclic stress ratio (CSR), a significant increase in the number of cycles to liquefaction was observed, from 125 to over 500. Furthermore, the development of excess pore pressure showed a similar trend for both

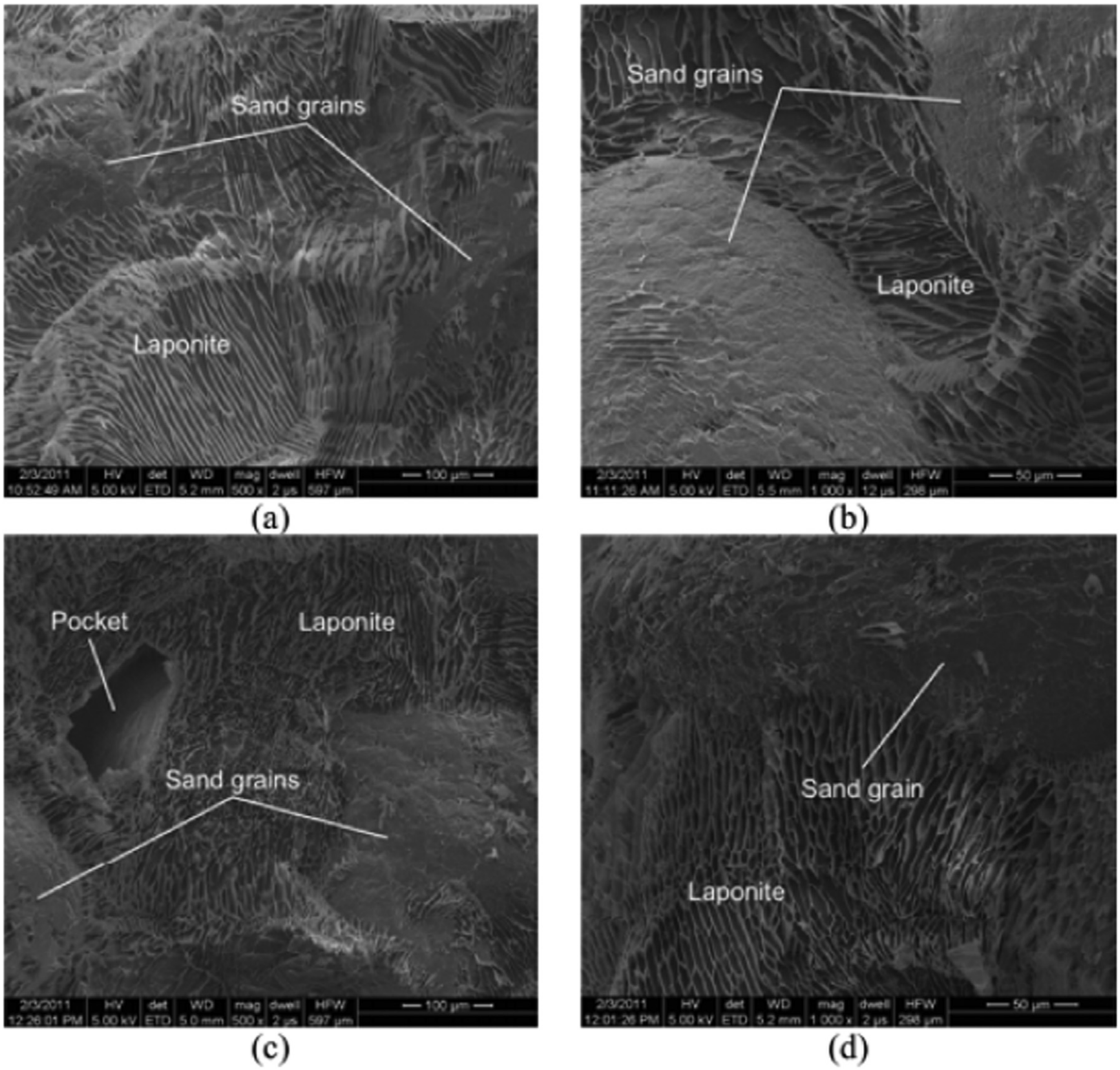

Fig. 12. Cryo-SEM of a 3% laponite (by mass of water) permeated specimen at (a) 500× and (b) 1000× magnification and a 1% laponite (by mass of sand) dry mixed specimen at (c) 500×, and (d) 1000× magnification [43].

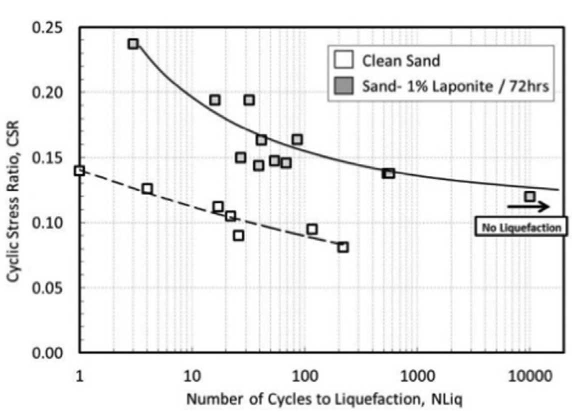

Fig. 13. Cyclic resistance of clean sand and sand-laponite specimens with Drsk~15–25% [31].

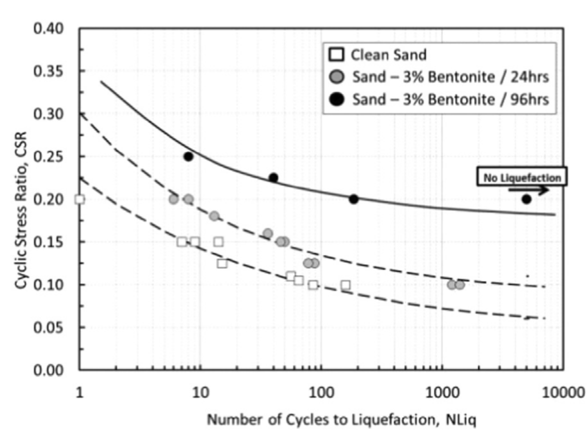

Fig. 14. Cyclic resistance of clean sand and sand-bentonite specimens with Drsk~30–40% [31].

specimens, where the development of excess pore water pressure appeared during the "plateau-stage" for a longer period compared with the clean sand sample (Fig. 16) [42]. To summarize, the use of laponite can effectively mitigate liquefaction without polluting the environment.

Overall, the three types of nanomaterials discussed in this section are shown to improve soil liquefaction resistance. The use of nanoparticles in soil mixtures increases strength, swelling index and compressibility, while decreasing permeability, liquefaction risk, settlement and volumetric strains. Soil strength improvement by the inclusions of

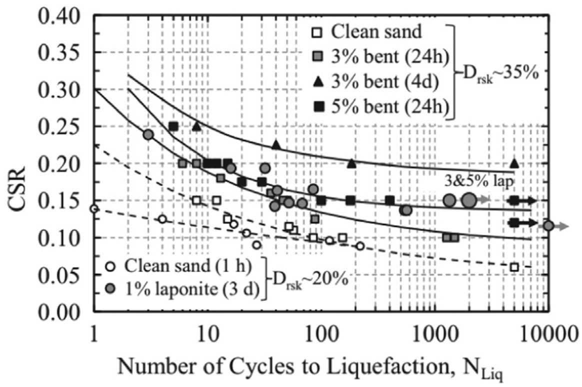

Fig. 15. CSR versus number of cycles to liquefaction: comparison between clean sand, sand-laponite and sand-bentonite specimens [42].

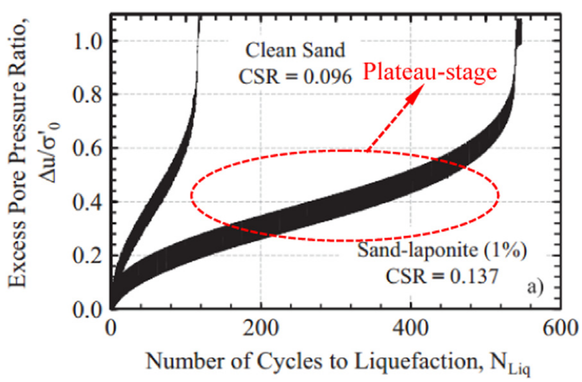

Fig. 16. Excess pore pressure versus clean sand and sand-laponite specimens at different CSR [42].

nanomaterials does not cause a large disturbance in the surrounding ground or structures and is an environment-friendly method. Furthermore, considering the cost of cement and chemical solutions, colloidal silica, bentonite, and laponite can be estimated to be an economical solution. According to the price/performance ratio report [18], nanomaterials have a better price/performance ratio than traditional chemical grouting materials despite their relatively high unit price. This is because only a small volume of nanomaterials is required for effective strengthening for the same grouting conditions and soil porosity. In these cases, the nanomaterials would completely fill the pore without any grouting waste in the soil treatment. In addition, it is expected that with the availability of advanced production techniques and improved manufacturing, the price of nanomaterials will also decrease in the future. Thus, as a new technology, the application of nanomaterials in geotechnical engineering will improve the economic and social outcomes.

2.2. Short synthetic fibers

The concept of soil reinforcement with natural fibers has been recognized for many years. However the use of randomly distributed fibers to reinforce soil has recently attracted a resurgence in research interest in geotechnical engineering [46,47]. Using randomly distributed fibers for liquefaction mitigation was proposed recently as a new method. Natural fibers can also be a good solution for improving liquefaction resistance because of low cost and pollution free. Nevertheless, the durability of natural fibers in the soil environment is much lower than synthetic fibers. Short synthetic fiber composite soil is still a relatively new technique in geotechnical projects. In these systems the load transfer mechanisms at the interface between the fibers and the soil, the influence the fiber orientation and fiber durability in complex

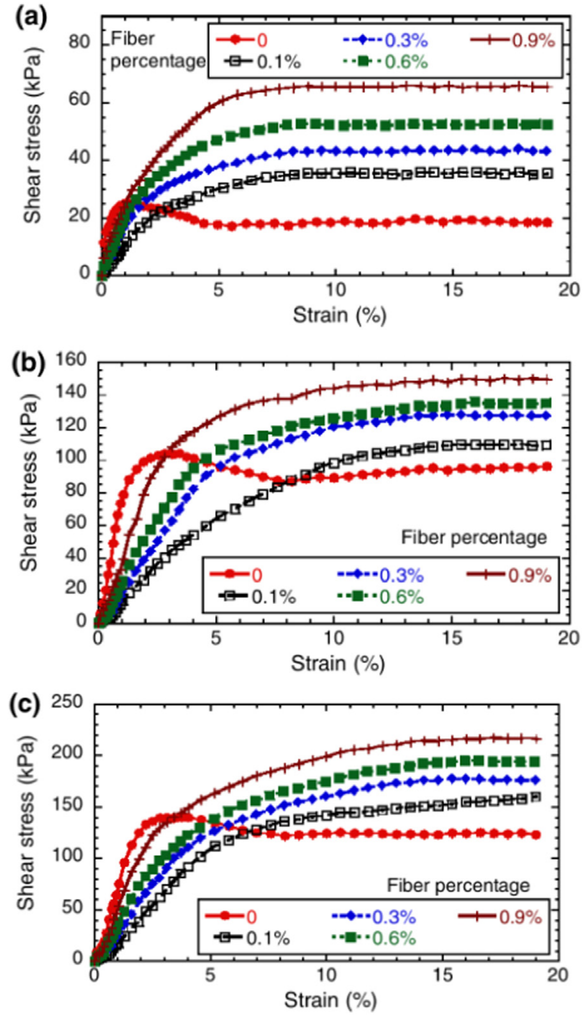

Fig. 17. Shear stress-strain curves of reinforced sand with different fiber contents and vertical normal stresses: (a) vertical normal stress σ_n = 50 kPa; (b) vertical normal stress σ_n = 150 kPa; (c) vertical normal stress σ_n = 250 kPa [50].

soil environments are not well understood.

Previous research [13,14] used direct shear and triaxial compression tests to study the effects of different species, content, direction and fiber orientation. The results showed that with increasing fiber percentage an increase was observed in the peak shear strength, axial strain at failure and ductility after failure, while the post peak reduction in shear resistance was restrained. Furthermore, the highest value of shear strength was obtained when the initial fiber orientation was 60° relative to the shear surface (Fig. 17) [46–52]. Some researchers explored the effects of fibers on the liquefaction resistance of sand by using traditional triaxial and ring-shear tests in order to understand the influence of different species, content and length of fibers on static liquefied sand [53–57]. From the tests' results, it was seen that with an increasing amount of fiber, the peak and residual shear strength continued to increase, while the initial stiffness and brittleness index reduced. The loose samples were not greatly influenced by the presence of fiber in undrained shear tests. For the medium dense sand, the enhanced effects became obvious. The sample converted from the strain softening response (typical for loose unreinforced sand) to the strain hardening response under undrained shear conditions.

Rashid et al. [58] and Haeri et al. [59] used fiber geotextile to study the mechanical properties of sand, and their results demonstrated that geotextile inclusion increased bearing capacity, axial strain at failure, ductility and reduced dilation in the geotextile layers. The influences of

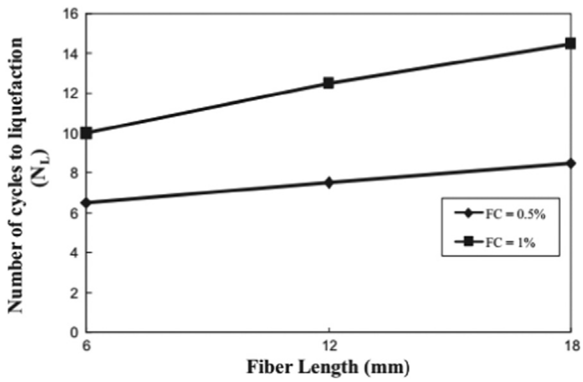

Fig. 18. Number of cycles causing liquefaction versus fiber length at various fiber contents (Dr = 40% and CP = 100 kPa; Dr is relative density, CP is confining pressure) [58].

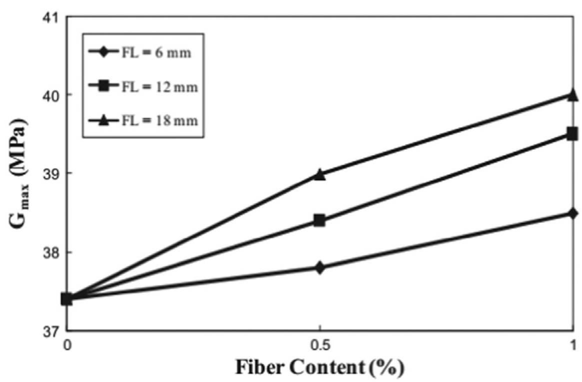

Fig. 19. G_{max} versus fiber content for different fiber lengths (Dr = 40% and CP = 200 kPa [60].

geotextile type, confining pressure and geotextile arrangement were examined. Noorzad and Fardad Amini [60] used cyclic triaxial tests to study the effects of randomly distributed fibers on liquefaction resistance and shear modulus of liquefiable sands (the loose and medium dense sand deposits). Test results indicated that with an increase in fiber content and length, the number of cycles to liquefaction and the shear modulus of sand increased (Figs. 18 and 19). The increase in the shear modulus was due to the addition of fiber, which also resulted in an increase in the sand stiffness. At the same time, the effect of the fiber treated medium dense sample was better than that of the loose sample. Now, studies of fiber-modified liquefiable sand have primarily focused on different fiber materials, length, direction, content, as well as ordered and disorderly placement. The influence of confining pressures and the relative density of sand were also studied through triaxial tests. The main mechanism of sand liquefaction mitigation was due to the presence of fibers in the voids and the formation of the random distribution of interlocking network structure, which resulted in better compaction of the sand matrix with added fibers [55,56,60,61].

In general, the enhanced toughness and ductility of short fiber treated soils are effective for improving liquefaction resistance, and it has been confirmed that the addition of fibers can significantly improve the liquefaction strength of sand [48,62]. This means that short synthetic fiber inclusions raised the number of cycles required to cause liquefaction during undrained loading. Moreover, fibers are cost competitive compared with other materials, and construction using short synthetic fiber reinforcement is not significantly affected by weather conditions. However, executive problems of soil reinforcement using short synthetic fibers in engineering practice are still to be solved. These include a lack of scientific standard in engineering practice, clumping and balling of fibers and adhesion between fiber and soil [48]. Further studies are necessary to elucidate the fracture mechanism, the effect of prior treatment of the fibers and the durability of the composites under more severe conditions.

2.3. Recycled materials

With the rapid development of society, the amount of waste materials such as tires, construction waste and glass have continued to rise. The disposal of these waste materials poses a significant threat to the environment. To solve this problem, some researchers began to use abandoned materials as backfills in geotechnical engineering to relieve liquefiable sand and restrain foundation deformation.

Hazarika et al. [63] added discarded tires, processed chips into sand, and used undrained cyclic triaxial tests to determine that the ability to resist liquefaction was significantly increased as the amount of tire chips (close to 50% by the total volume of sands) increased (Fig. 20). Although the increase in the proportion of tires resulted in a significant reduction in relative density, the presence of tires can reduce the accumulation of pore water pressure. Seismic waves were found to gradually decay due to the increasing damping ratio in liquefiable sand and liquefaction did not occur when using tires as backfills under earthquakes [64,65]. Bahadori and Manafi [66] conducted a series of 1 g shaking table model tests to study the effect of different contents of tire chips in saturated sand. The results show that pore-water pressure generation and settlement was reduced, while the damping ratio was augmented with an increasing content of tire chips.

Glass fiber, as an abundant renewable resource with minimal hazards to the environment, was also investigated. Ates [67] used the direct shear tests and unconfined compressive strength tests to demonstrate optimal mechanical properties of cement treated sand with 3% glass fiber. At the same time, the strength increased with curing time because the cement filled sand grains and the glass fiber covered all the sample area. The distribution and stretching of fibers around the sand improved the tensile or pull out strength that resulted in a flexible constraining and reinforcement against the brittle breakage of cemented bonds and raised the ductility of samples during axial or shear deformations (Fig. 21) [68].

To mitigate the liquefaction-induced problems of embedded lifelines (Fig. 22) at shallow depths, Otsubo et al. [69] considered the use of waste/recycled materials as new backfills in their shaking table tests. The study included crushed glass, crushed concrete, mixture of tire chips and silica sand, and cement-mixed liquefaction ejection. All the employed materials were recycled or reused to meet the economic and ecological requirements. The results showed that construction of backfills with recycled materials demonstrated satisfactory performance in preventing the floating of the pipe. Based on these studies, liquefaction mitigation using tire chips was recommended due to its good permeability, ease of compaction and effectiveness in minimizing the displacement of the pipe due to its balanced unit weight, even with liquefied surrounding subsoil. It was also suggested that recycled crushed glass and crushed concrete were suitable for use as backfill materials.

In summary, liquefaction mitigation using waste/recycle materials is an effective and environment-friendly method that conserves resources. Some recycled materials such as scrap tire chips are gradually being applied in on-site engineering practices. Although some additives may affect the environment after demolition of the constructed earth structure, the above-mentioned methods using different recycled materials have potential as non-disruptive, low-cost and environment-friendly methods to improve liquefaction resistance that is applicable to large areas. However, the majority of these studies are currently at the experimental stage only [16].

2.4. Biological materials

Another environment-friendly technology is using biological

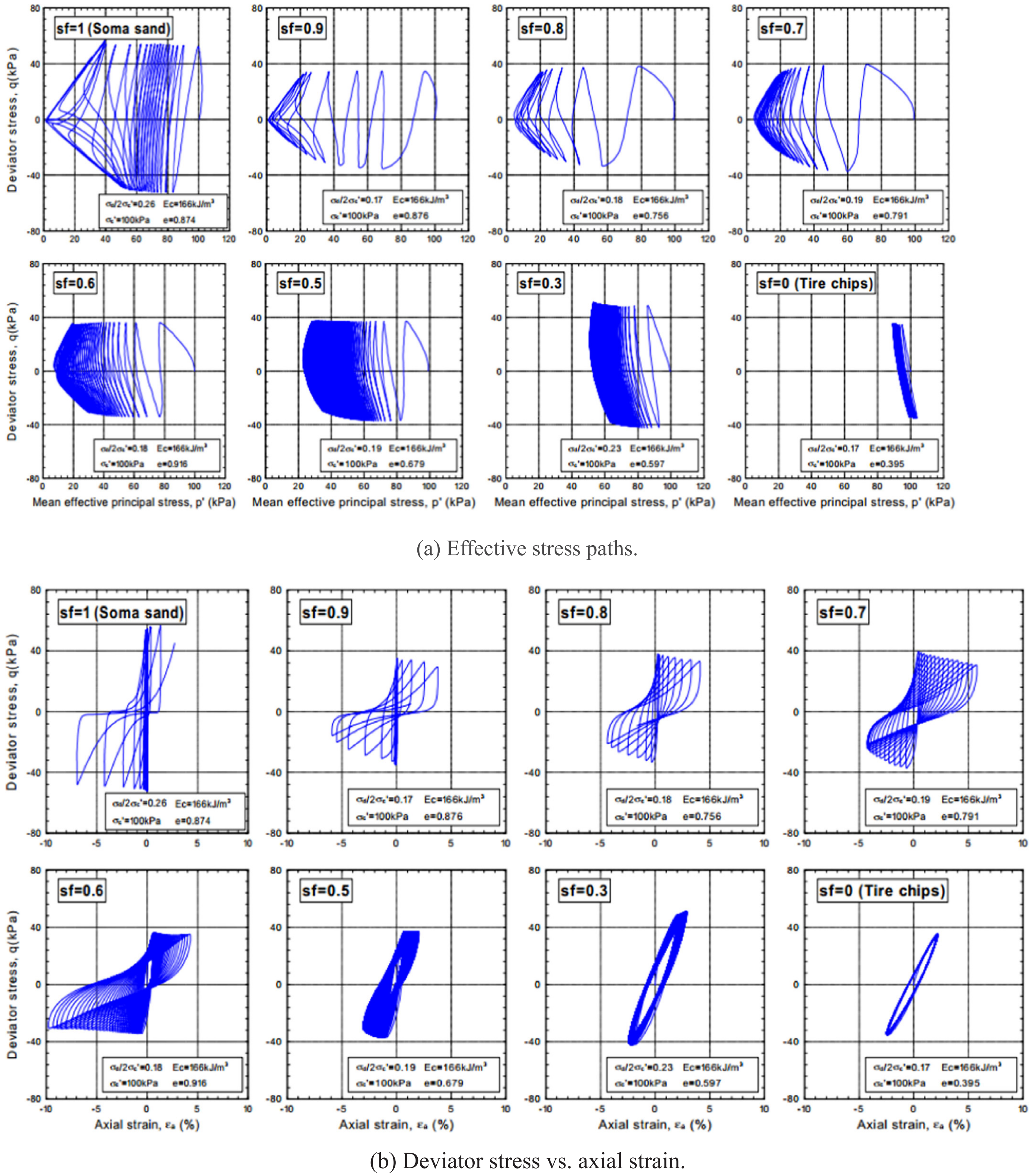

Fig. 20. Typical results of undrained cyclic shear tests (a) Effective stress paths; (b) Deviator stress vs. axial strain (*sf* = 1 indicates samples consisting of sand only, while *sf* = 0 represents sample with tire chips only) [63].

materials. Sandy soil treated with biological materials has become a popular research subject in recent years. Treatment processes using biological materials offer an alternative and novel ground improvement method to reduce the liquefaction risk and prevent damage associated with earthquake loading [70].

The main mechanism of biological materials is the processes of using microorganisms, nutrients and biological naturally induced calcite precipitation (MICP) with urea and a dissolved calcium source [71], so that the sand particles bond together. This process could be called "biocementation". The main factors affecting calcium carbonate

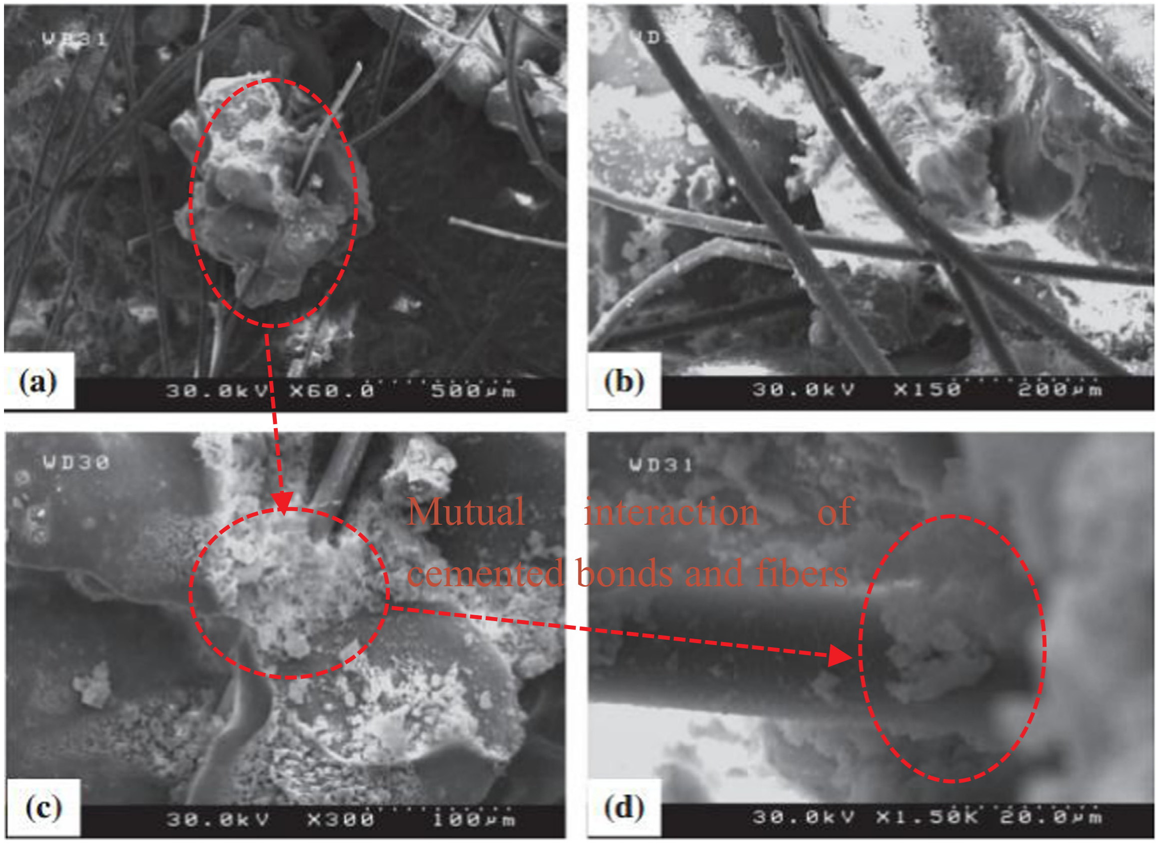

Fig. 21. Scanning electron micrographs of fiber-reinforced-cemented sand–gravel mixture with different scales (a): 500 μm; (b): 200 μm; (c): 100 μm; (d): 20 μm [68].

precipitation are the number of microorganisms, total volume of nutrients injected, porous media properties and pH value. Under these conditions, microorganisms automatically perform a series of biological reactions in the soil. Eqs. (1)–(3) present a reaction where urease was used to react with water to increase the pH value, thereby inducing the precipitation of calcium carbonate. In addition, the surface of the microorganisms has a negative charge, resulting in nucleation on the cell surface as shown in Eqs. (4–5) [71]. It was confirmed that MICP could be an effective, pollution-free and environment-friendly liquefaction mitigation method for sand. However, due to the transfer of microorganisms into the soil, the permeability conductivity of the soil was affected, resulting in the unsatisfactory transfer of microorganisms. Zamani and Montoya [72] found that with an increase in microbial content, the calcite in the soil was continuously precipitated (Figs. 23 and 24) and the permeability coefficient was reduced [73]. Han el at. [74] used dynamic triaxial experiments to study the dynamic behavior of microorganisms in soil. The results showed that under the cyclic loading, the liquefaction resistance, strength and stiffness of the sand treated by the microorganism were increased, while the generation of pore water pressure and the settlement of the foundation was reduced [70,74–76].

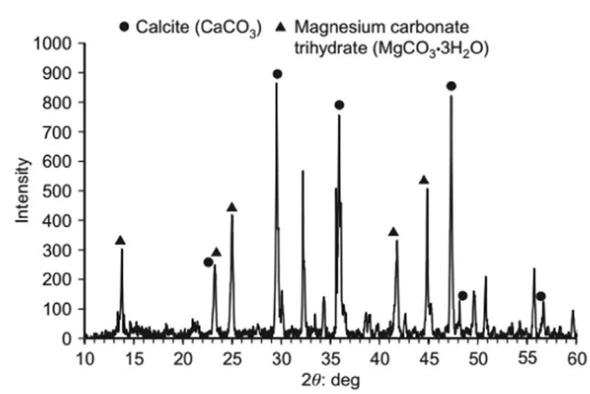

Fig. 23. X-ray diffraction pattern of precipitated crystal sample [73].

Simultaneously, a new technology, enzymatically induced calcite precipitation (EICP), emerged to treat liquefiable sand [77]. This technique uses urease directly as the promoter for hydrolysis of urea instead of using bacteria, resulting in calcium ions and carbonate ions

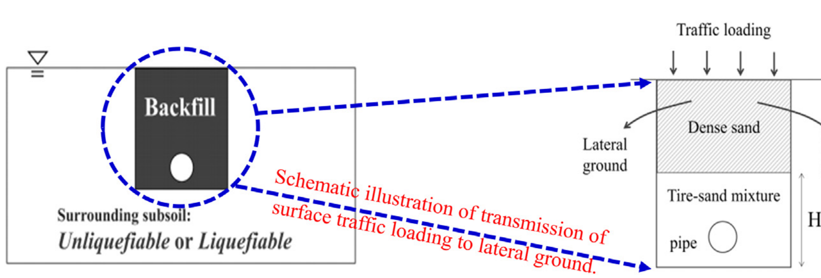

Fig. 22. Situation of surrounding subsoil with and without liquefaction [69].

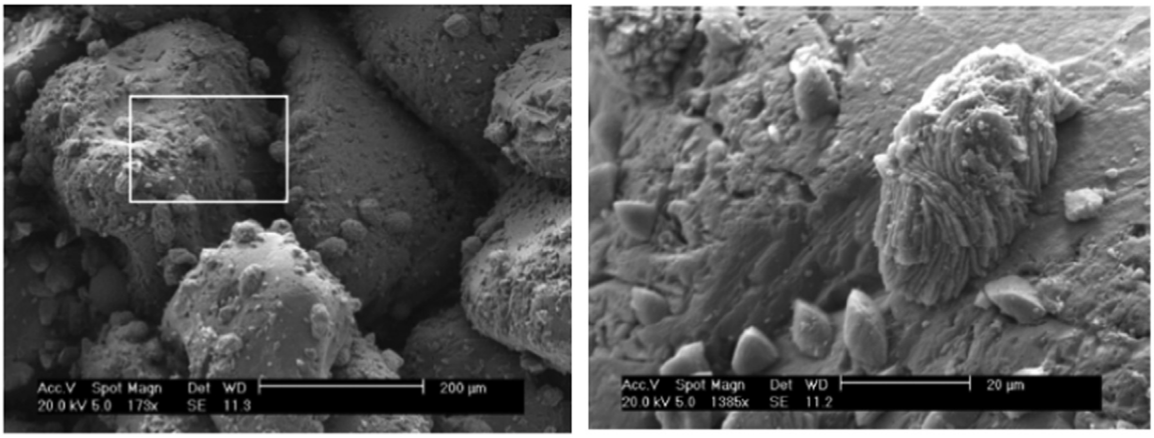

Fig. 24. SEM of the MICP treated sand sample with seawater (unconfined compressive strength 150 kPa) [73].

precipitating calcium carbonate. The experimental results found that at lower degree of saturations, the use of EICP could precipitate more calcites than saturated soil samples.

$$NH_2-CO-NH_2+3H_2O \rightarrow 2NH_4^{+}+2OH^{-} + CO_2 \quad (1)$$

$$Ca^{2+} + HCO_3^{-} + OH^{-} \rightarrow CaCO_3\downarrow+H_2O \quad (2)$$

$$Ca^{2+} + 2HCO_3^{-} \rightarrow CaCO_3\downarrow+CO_2+H_2O \quad (3)$$

$$Ca^{2+}+Cell \rightarrow Cell-Ca^{2+} \quad (4)$$

$$Cell-Ca^{2+} + CO_3^{2-}\rightarrow Cell-CaCO_3\downarrow \quad (5)$$

Although the acceleration of the earthquake motion when transferred to the ground surface was enlarged by using the above mentioned biological materials as a ground improvement method to improve liquefaction resistance, liquefaction induced ground deformations and foundation settlements during earthquakes were effectively reduced. Investigation on how to achieve a balance between the liquefaction resistance for soil and reduction of acceleration at the ground surface is needed. Overall, this method exhibited a very good example for liquefaction mitigation in an environment-friendly way.

2.5. Chemical grouting

Chemical grouting can significantly improve the liquefaction resistance of sand under the static and dynamic loads that cause liquefaction. Previous research has mainly focused on the study of shear strain amplitude, grouting type, concentration, durability and curing conditions. However, it is known that cement is used extensively for the stabilization of sandy soils to improve liquefaction resistance. This is considered to be very significant in geotechnical engineering, especially using cement as the bounded material in composite soil samples. According to previous results [78], the hardening effect and the impact of inter-particle cementation produced by cemented materials with a miner-based grout can not only resist the first earthquake, but also have an obvious effect on resisting aftershocks. Besides cement, lime stabilization was also developed followed by cement stabilization. Additives such as fly ash and phosphogypsum can be introduced to the lime soil and cement soil mixtures to further enhance the properties of the stabilized soil.

Maher et al. [79] used resonant column and cyclic triaxial tests to investigate the effect of different materials used for chemical grouting (sodium silicate, acrylate polymer, polyurethane) on dynamic liquefied sand. The tests' results showed that sodium silicate had a large shear modulus and little effect on damping ratio. Acrylate polymer had no effect on the shear modulus, but the damping ratio increased significantly. In addition to an increase of shear strain amplitude, ranging from 10^{-4} to 1%, the shear modulus of grouting sand decreased and the damping ratio increased (very rapidly). Saito et al. [80] used a series of indoor experiments to determine the long-term durability of chemical grouts. From the experimental results, it can be seen that the grouted sand can maintain long-term durability in the condition of continual inflow of groundwater with no change to the unconfined compressive strength over a curing period of 360 days. Porcino et al. [81] used a cyclic triaxial experiment to explore the effects of two-cycle phases of moderately chemical grouting sand. The report results of two-cycle

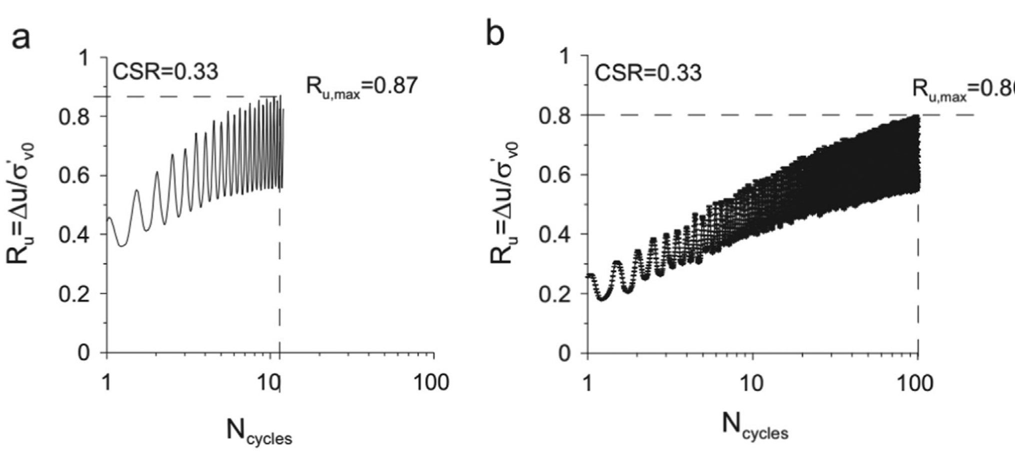

Fig. 25. Pore water pressure build-up during undrained cyclic SS (simple shear) tests of grouted TSM (Ticino river) specimens: (a) virgin and (b) after pre-shearing (I_r = 45%, σ'_{v0} = 100 kPa), I_r is initial density index, σ'_{v0} is effective vertical consolidation stress [81].

phases showed that the establishment of pore water pressure was significantly slower than the virgin sandy soil (Fig. 25).

2.6. Microfine cement

The commonly used Portland cement cannot be grouted into the micro-cracks of soil with small particle size. Thus, only microfine cement or superfine cement can be injected into fine sand with a permeability coefficient lower than 10^{-2} cm/s, but with the advantages of high strength, good durability and non-toxicity [82]. Microfine cement has an extremely high fluidity and bleed resistance due to its small particle size ($D_{95} < 16\,\mu m$) [83–85] and can overcome the pollution problems caused by chemical grouts [86]. The first commercially available microfine cement was MC-500, manufactured by Onoda Cement Corporation in Japan [87], while much finer cement products are being produced at present. A number of studies have documented the engineering properties of microfine cement grouted sand, including unconfined compressive strength, permeability, grouting properties as viscosity, setting time and stability [84,88–90].

Torsional resonant column and bender element tests were used to explore the difference between microfine cement and ordinary cement for factors such as confining pressure, shear strain, water-to-cement ratio, cement type and gradation on the dynamic properties [91]. The experimental results found that the water-to-cement ratio of microfine cement grouting material had a significant influence on the dynamic performance of the soil, but had a relatively small impact on ordinary cement. Thus, the water-to-cement ratio of microfine cement was investigated by many researchers [82,83,88,92,93]. The results showed that with a decrease in the water-to-cement ratio, the viscosity of the slurry, storage modulus, unconfined compressive strength increased while the settling time and permeability decreased. However, the pressure of the slurry injection would continue to increase. Delfosse-Ribay et al. [86] used the creep test to measure the durability of the microfine cement grouting soil. The investigational results showed that the axial strain of the soil was significantly reduced, and after 200 days of experimental testing, the creep strain remained unchanged.

Obviously, the main influencing factors affecting the penetration of microfine cement are water-to-cement (W/C) ratio, soil particle size, pore size, and cement type. The use of microfine cement grouting can effectively improve the strength of the soil and increase the penetration range. Additionally, there is no damage to the surrounding structures and environments. Although the production cost is high, the fine cement slurry has strong permeability and provides good reinforcement, and the overall economic benefit is higher than that of ordinary cement grouting [84].

2.7. Partial saturation method

In recent times, research has focused on the exploration of liquefiable sand. Additionally, it was demonstrated that the liquefaction resistance of unsaturated sand is much higher than that of saturated sand [94–96]. As a result, many studies have used various means to induce partial saturation of sand because of its low-cost and applicability in the closely constructed residential areas. This technique may be divided into five categories: air injection, biogas produced by bacteria in the soil, electrolysis, sand compaction pile and chemical methods to produce tiny gas bubbles in-situ from nutrients (Fig. 26) [97–102].

Zeybek and Madabhushi [102,103] used a series of centrifuge model tests to assess the effect of sand saturation on liquefaction below shallow foundations by air-injection. The results indicated that the excess pore water pressure was restrained, the average settlement of the structure was reduced and the liquefaction resistance increased, especially at high confining pressure. However, a larger acceleration was converted to infrastructures through the non-liquefied area [104]. To reduce the saturation of soil, materials (e.g. methanol, ethanol or sodium acetate) were used as electron donors to produce small amounts of nitrogen and carbon dioxide through a microbial de-nitrification process (Fig. 27) [105,106]. The reaction formula is Eqs. (6)–(8) as follows:

$$5CH_3OH+6NO_3^-\rightarrow 3N_2+5CO_2+7H_2O + 6OH^- \tag{6}$$

$$5C_2H_5OH+12NO_3^-\rightarrow 6N_2+10CO_2+9H_2O + 12OH^- \tag{7}$$

$$5CH_3COO^- + 8NO_3^-\rightarrow 4N_2+10CO_2 + H_2O + 13OH^- \tag{8}$$

The tests' results showed that the gas produced by microorganisms could reduce the saturation degree of sand to 80–95%. Yegian et al. [101] induced partial saturation of the sample through electrolysis and drainage recharge of the pore water. Their results showed that the sample saturation decreased significantly, and the changes in saturation were small over time. With decreasing saturation, the undrained shear strength of samples continuously increased (Fig. 28), and the pore water pressure decreased (Fig. 29). Moreover, the stress-strain relationship of loose sand could change from strain softening to strain hardening [107–109].

The method of biogas, using microbial denitrification in liquefaction resistance engineering, has been widely applied to wastewater treatment. Compared to other desaturation methods, treatment using the biogas method can make smaller and more evenly distributed gas bubbles in the pore water which are less likely to escape from the foundation. Additionally, this method is energy-efficient and can achieve improvement in liquefaction resistance without recompacting the foundation. Moreover, biogas causes minimal disruption to the site and can be applied to existing and vulnerable structures [105].

Mudflow-type slope failures caused by earthquakes have attracted attention worldwide in recent years. It was suggested that these failures were related to the liquefaction of unsaturated soil. This means that unsaturated soil would also liquefy completely when both the pore air and water pressure are equal to the initial mean total confining pressure. Furthermore, the possibility of liquefaction in unsaturated sand subjected to cyclic earthquake loads was proved by laboratory experiments and numerical simulations [110–112]. Thus, the effects of the induced partial saturation method for liquefaction mitigation need further investigation.

Overall, induced partial saturation method by air injection, biogas or chemical approach has been proposed as a possible countermeasure against liquefaction. These techniques may be applied to closely constructed residential areas and have been confirmed to be effective for preventing liquefaction. However, there are still many problems to be solved before application to real world engineering projects. One of the key factors is the stability of the partial saturation effect because the underground water is a whole system that the small gas bubbles might connect with to escape from the designed soil area. Thus, it is important to ensure that the long-term improvements in liquefaction resistance are sustainable when considering the induced partial saturation method.

2.8. Other materials

A number of research groups have begun investigating new materials as alternatives to cement or lime that are used as bounding materials. This is done to minimize environmental pollution that may arise from the use of large amounts of cement and lime and to promote sustainable development. One such material is ash (FA), which is comprised of silica and alumina. The particles are a porous honeycomb structure and the specific surface area is large, with higher adsorption activity and particle size range of 0.5–300 μm. Fly ash may be added in the liquefiable sand as a filler material, while also playing a role as a chemical additive to improve liquefaction resistance of sand [113]. Keramatikerman et al. [114] conducted a series of triaxial experiments to determine the relationship between liquefaction of sand and fly ash. The results showed that the use fly ash could significantly enhance the

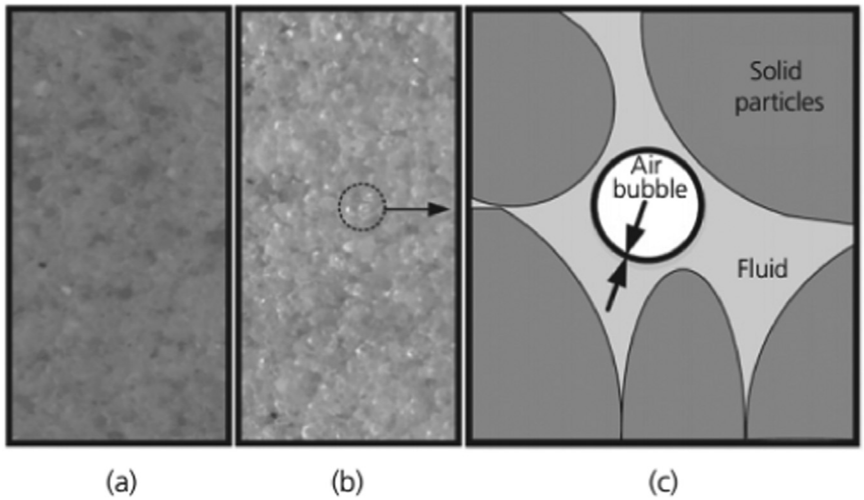

Fig. 26. Soil condition (a) before air injection, (b) after air injection and (c) state of air bubbles [102].

liquefaction resistance of sand. The test results showed the increase of curing time led to a further enhancement in the liquefaction resistance. In addition, with the increase in confining pressure (CP), the number of cycles to liquefaction continued to decrease (Tables 1–2). Moreover, Sabbar et al. [115] used bentonite and slag which are easy to obtain, cheap, economic and environmentally safe material compared to other cementing agents, to study the static liquefaction behavior of sand. The tests showed that in a loose sand-slag-bentonite mixture, the inter-particle voids were filled by slag and bentonite, which significantly improved the liquefaction resistance and reduced the pore water pressure. In addition, the undrained brittleness index, I_B, which was defined as the ratio of decrease in the maximum deviator stress, decreased dramatically (Fig. 30). Mola-Abasi and Shooshpasha [116] used unconfined compressive strength tests to investigate the relationship between zeolite and cement additives on the mechanical properties of sand. The main components of natural zeolite were silica and alumina,

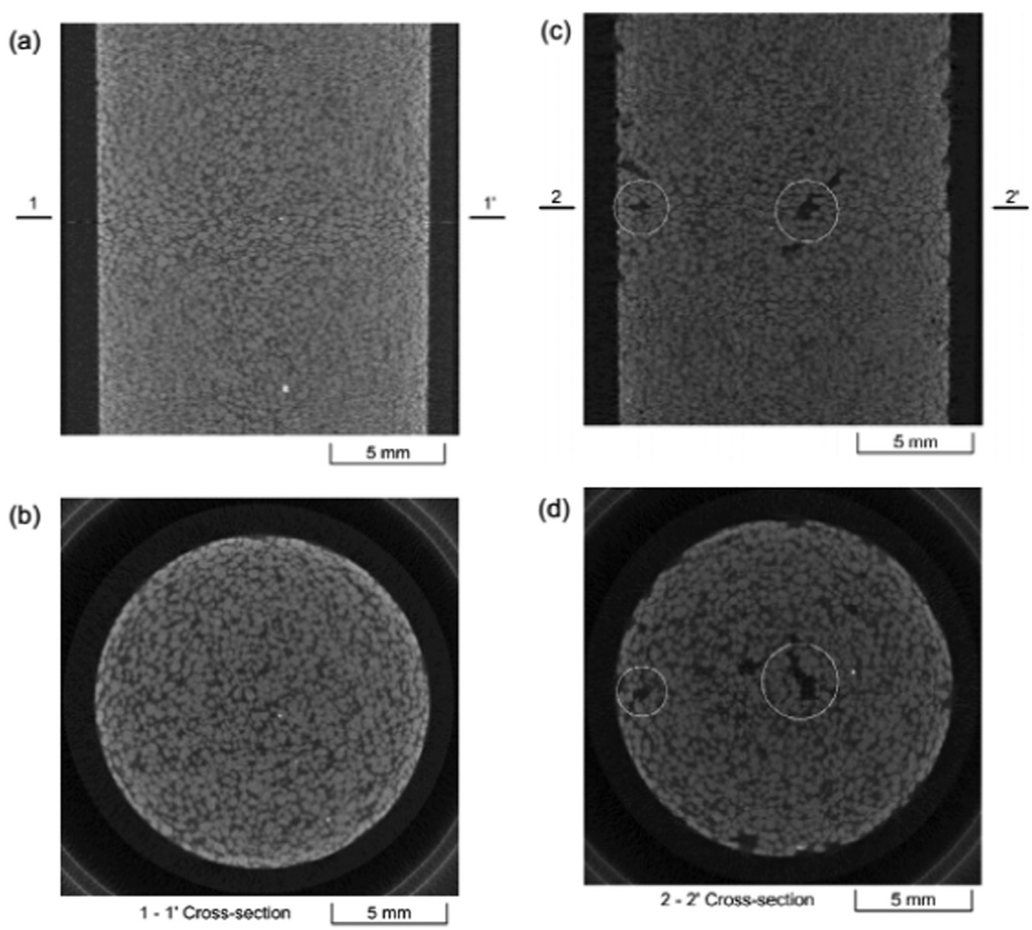

Fig. 27. Computer tomography (CT) images of saturated and desaturated soils (a) and (b): saturated soil; (c) and (d): desaturated soil with 94% saturation degree [106].

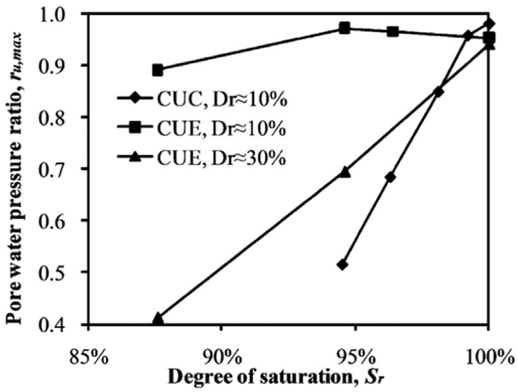

Fig. 28. Pore water pressure ratio versus degree of saturation [107]. (Consolidated undrained compression, CUC, and extension tests, CUE. The pore water pressure ratio is expressed as the ratio of the maximum pore water pressure during shear to the initial effective confining stress $r_{u,max} = u_{max}/p'_0$).

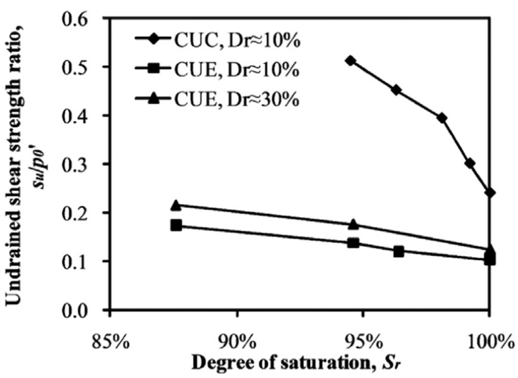

Fig. 29. Undrained shear strength ratio versus degree of saturation (The undrained shear strength ratio is defined as the ratio of undrained shear strength obtained from an undrained test to the initial effective confining stress: s_u/p'_0) [107].

Table 1
Effect of relative density on liquefaction strength of the untreated soil and sand mixed with 2% FA under 50 kPa CP and 0.2 CSR and 1 Hz frequency [114].

No.	Specimen	Confining pressure, CP (kPa)	Relative density, D_r, (%)	Number of cycles to liquefaction, N_L
1	Untreated soil	50	20	175
2			40	275
3			60	300
4			80	325
5	Sand + 2% FA	50	20	290
6			40	350
7			60	375
8			80	450

very similar to pozzolanic materials. Tests' results showed zeolite could effectively replace part of the cement to enhance the strength of the sand by a pozzolanic reaction with calcium hydroxide. The substitution of zeolite for part of the cement could increase the unconfined compressive strength of the sample. Even if the amount of cement used was very small, the unconfined compressive strength would increase with the increase of zeolite replacement content. Naseri et al. [117] studied the performance of graphene oxide nano-sheets (high specific surface area and surface charges with fine pores) on the impact of silty soil through mechanical experiments. The results showed that the cohesion and internal friction angle of samples continuously increased with an increase in concentration of graphene sheets and curing time (Fig. 31), while the pores of the soil samples decreased due to the interface

Table 2
A summary of the results to investigates effect of the 4% and 6% FA addition on liquefaction strength of the sand with 20% relative density and under 50, 70 and 90 kPa confining pressure [114].

No.	Specimen	Confining pressure, CP (kPa)	Relative density, D_r, (%)	Number of cycles to liquefaction, N_L
1	Sand + 6% FA	20	50	350
2			70	325
3			90	250
4	Sand + 6% FA	20	50	375
5			70	350
6			90	275

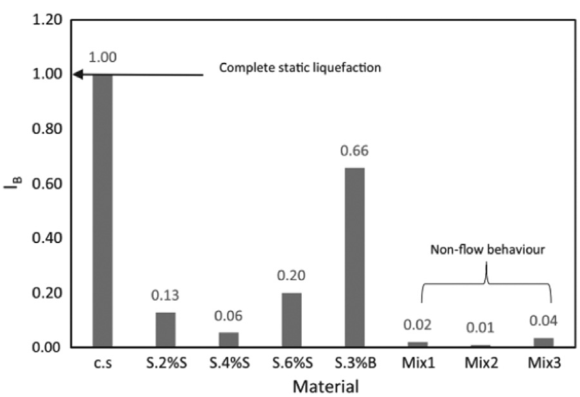

Fig. 30. Variation in I_B for all materials with Dr = 10%, B = 0.95 (B is saturation of sand sample), and initial confining pressure of 100 kPa (C.S is Clean sand; S.S is sand and slag; S.B is sand and bentonite; Mix1: Sand + 3% Bentonite + 2%; Slag Mix2: Sand + 3% Bentonite + 4% Slag; Mix3: Sand + 3% Bentonite + 6% Slag) [115].

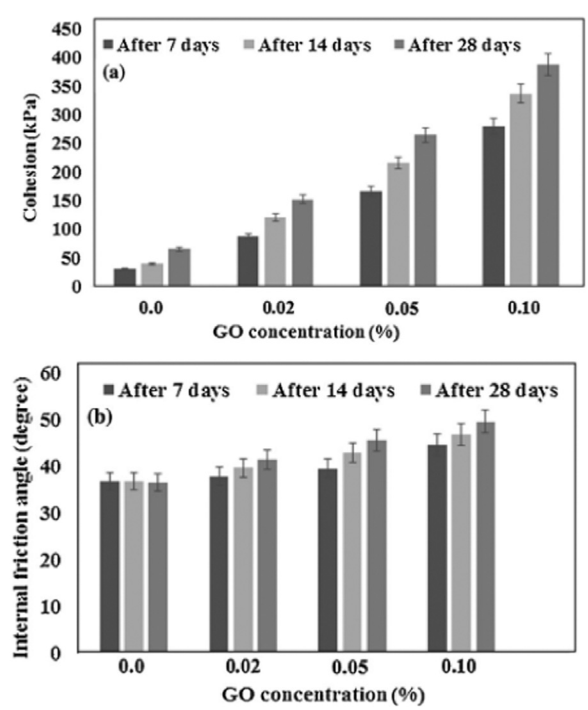

Fig. 31. (a) Cohesion and (b) internal friction angle values of the soil samples [117].

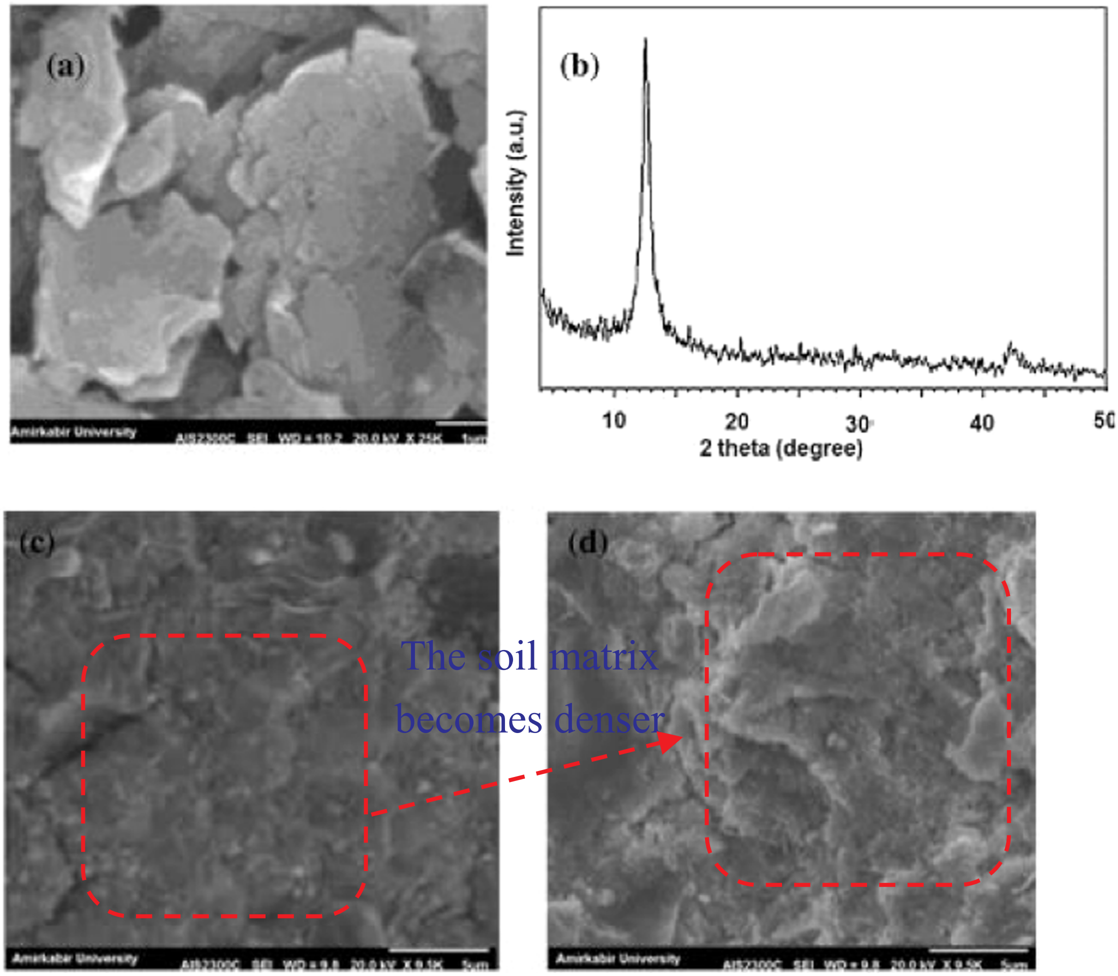

Fig. 32. (a) SEM image and (b) XRD pattern of synthesized GO, (c) SEM image of soil/cement and (d) SEM image of soil/cement/GO 0.05% [117].

bonding between the GO (graphene oxide nano-sheets) and formation of C–S–H gel (Fig. 32).

3. Applicability

The main problem to be solved for each liquefaction mitigation method is to control the rapid growth of pore water pressure in the soil. Current liquefaction mitigation methods could be divided into three types to effectively control the pore water pressure: (i) reduce the volume of pore occupancy [15]; (ii) enhance the cementation force between soil particles; (iii) reduce the saturation of the soil [97,103]. The current methods to achieve these pathways fall into two broad categories: (i) Infiltration, including natural infiltration and passive infiltration [20,21]; (ii) Mixing of reinforcement materials and soils [62,115]. Therefore, the best approach varies with the application in different pore size of soil. At the same time, the different methods to reduce pore water pressure will affect the uniformity of the distribution of the reinforcement materials and bring disturbance to nearby structures in different extent. In addition, for the application, the methods of injection, nanomaterials treatment, biological reinforcement, chemical grouting, desaturation technologies are suitable for practice in existing ground, while fibers and recycled materials treated soils that may affect the environment after demolition of the constructed earth structure, are feasible in new earth filling.

3.1. Pore size of soil

For coarse-grained soils with large pores, nanomaterials, chemical materials, microfine cements, and biological materials can penetrate effectively. However, penetration is difficult for fine-grained soil, since the pores of the soil are small. In summary, nanomaterials are suitable for use in soils with pores above the nanometer scale [20,32,34]. The nanoparticles can easily disperse in the pore space between the soil grains, especially in fine soil that is not under high pressure [18]. Chemical materials [81] and microfine cement materials [84] are suitable for use in soils with pores above the micron level (particle size greater than 16 μm). Fine-grained soil with pores less than 0.4 μm prevent the effective penetration of biological bacteria, because fungi and protozoa need to be larger than 0.6 μm to be effective [71].

For materials that are directly mixed and backfilled with soil, the method might be suitable for use in soils with various pore sizes. However, it is necessary to make corresponding judgments according to different performance requirements. For the partial saturation method by air injection, layers of lower permeability (e.g. silts and clays) may limit its effectiveness. In general, the method is best suited for sites with sandy soils having hydraulic conductivities of 10^{-4} or 10^{-3} cm/s or greater and is typically used at depths of less than 10–20 m [118].

3.2. Disturbance to nearby structures

According to the current liquefaction mitigation methods, one of the main factors causing disturbances to surrounding structures is high pressure passive infiltration. In the actual project, in order to uniformly bring the reinforcing material to the desired place, e.g. chemical grouting or microfine cement grouting, it is impossible to simply rely on the natural infiltration method. Instead, high pressure injection is required to effectively penetrate to depths where reinforcement is required. Therefore, infiltration is generally carried out by means of high pressure injection. However, it will cause deformation of the soil during the reinforcement process and disturb nearby structures due to the excessive pressure of the injection [20,79]. Even with this high pressure technique, the reinforcing materials cannot penetrate uniformly into the soil.

The nanoparticle-water suspension has a lower initial viscosity, thus this new method is applicable to bare ground as well as to developed areas surrounded by buildings and constructions. Compared with the traditional methods, the nanoparticle-water suspension method can penetrate more evenly in soil and greatly reduce the disturbance to the surrounding environment as it does not require a high-pressure infusion [45].

Chemical solutions can be injected in fine sands or coarse silts by high pressure injection, but are more expensive and some of them pose health and environmental hazards. For example, the degradation silicate grout releases large concentrations of soda and organic derivatives. These toxic substances may cause environmental and ground pollution. The application of some chemical grouts is limited because of their high cost, permanence and toxicity.

Relatively few practical methods are currently available for liquefaction mitigation beneath existing structures. It is difficult to control ground deformation in the constructions. However, recently in situ reports have revealed that some injection under existing structures was confirmed to be available. Based on the field tests at the project site that suffered liquefaction-related settlement damage in the 2010–2011 Canterbury earthquake sequence, soil improvement using injected expanding polyurethane grout is applied successfully beneath existing buildings, without necessarily interrupting the use of those building, although soil heave and lifting of the building floor were observed in all cases of ground injection [119]. The injection of expanding resin is also reported to be feasible for liquefaction mitigation beneath existing structures while there was no attempt made to control ground heave. Ground heave and general surface disturbance using resin injection were observed to be noticeably less than that for other technologies such as stone columns or driven piles through field investigations [120]. In another hand, considering the various site restrictions, compaction grouting was chosen as the most practical method to strengthen the foundation ground and the merits of compaction grouting as a convenient method of ground improvement under existing structures were discussed [121].

3.3. Uniformity in soil

Experimental studies have shown non-uniformity of the soil gas and the unevenness of the penetration of the slurry material during the liquefaction mitigation [20,109]. Centrifuge and shaking table tests results reveal that the distribution of air bubbles is not completely uniform, and the higher the air injection pressure, the wider and more uniform the effective air-entrapped zone [103,122]. Sparging of air under high pressure might disturb the granular structure of sand. Thus, some measures can be taken to avoid high pressure sparging or alleviate structure disturbance [123–125].

However, the uniform distribution of gas cannot be efficiently examined, and the successful soil improvement by gas can not be confirmed. In some cases, the extent of the improvement is not reflected for in-situ test results until a period of time after the improvement has been completed. For the air injection method by sparging, a higher flow rate improves the air distribution. In other words, to be effective and uniformly distributed, air must be continuously or frequently introduced. As currently envisioned, the air injection method would be feasible for structures with limited access since air is injected, rather than grout [103,118].

On the other hand, a series of experiments studied the effects of groundwater flow on the flow patterns of injected air. The air flow patterns observed are found to depend significantly on the soil type and groundwater flow conditions [126]. The shape of the injected air zone of influence is not affected by groundwater flow when the hydraulic gradient is less than or equal to 0.011 [127]. Recent laboratory and pilot-scale research have shown that the effectiveness of air sparging is often limited by a number of factors in practice. One major constraint is the impact of “channeling” on air movement during sparging [128]. Air injected into saturated porous soils frequently moves in discrete channels that comprise only a fraction of the entire cross-section of the zone, rather than passing through the whole medium as bubbles. This channeling phenomenon greatly reduces the “stripping efficiency” of air sparging. The physics of air bubbles movement under water are not widely understood and the movement is extremely sensitive to formation structure [124].

Although many in situ tests results reveal that the degree of saturation of soils after several years is noticeably, not significantly, higher as compared with that shortly after ground desaturation, some have survived for decades, and the longevity of air bubbles injected into the improved soil and evaluation of effectively desaturated zone is confirmed through field tests [100,129]. Anyway, the ground water flow may remove with time the injected gas from the target subsoil. There is no appropriate technology to capture the time-dependent loss of reduced saturation.

4. Cost

According to current research on liquefaction mitigation methods, the main research trends are to identify techniques that are cost effective, environmentally friendly and sustainable. However, it is hard to estimate the cost accurately because the whole cost is related to many factors, including price of unit material, dosage, construction method, construction machine, effectiveness and environmental impact. Quantitative cost assessment is difficult to obtain. The reasons are: (i) most of these methods are still in the stage of laboratory investigation and not used for the on-situ construction, thus cost can not be easily evaluated; (ii) For the used methods in practice, the cost depends on treatment range of soil, deposits condition, labor cost that varies in different area or countries, construction difficulties and used machineries, construction time transportation, waste disposal, etc. These are complex factors and make it difficult to estimate the cost quantitatively. Similar issue was also addressed in the existing study that the costs of these methods vary widely, and the conditions under which these methods can be used are influenced by the nature and proximity of structures and constructed facilities [130]. Therefore, this review just gives a simple description about cost assessment that if these methods are cost-effective or not according to existing literature.

(1) For using nanomaterials, the unit cost is high but the overall cost performance or price/performance ratio is higher than that of cement grouting and chemical grouting materials when considering the superior properties of nanomaterials, such as good permeability and high strength of reinforced soil, minimal disturbance to surrounding ground and structures and environmental impact [45].
(2) For fiber-reinforced soils, the cost is competitive compared to cement, lime, and chemical materials, but fiber-reinforced soils have the advantages of easy operation, good reinforcement effect, high durability and construction are unaffected by weather conditions [50,131].
(3) For using recycled materials, production cost of recycled materials is low. Their use may have an environmental benefit by reusing materials that would otherwise be disposed of in landfill. Therefore, the use of recycled materials has low economic costs, when their application is suitable [69,116,132]. Tire waste was also found to be effective as soil reinforcement beneath footings, embankments and retaining walls. Findings lead to overall saving in soil material costs and reuse of tire waste.

(4) For microfine cement method, although the production cost is high, the fine cement slurry has strong permeability and good reinforcement effect, and the overall cost is lower than that of ordinary cement grouting [84].
(5) For the using of biological materials, including biocementation or biogas, the processes of biocementation or biogas are cost-effective and have a lower environmental impact compared to chemical grouting, which is usually costly and toxic for environment [17]. However, microbial processes are complicated and only applicable to certain soil types and site environments.
(6) For partial saturation by air injection, higher flow rates can improve the resulting air distribution but increase the compressor requirements. As currently envisioned, the air injection method would be feasible for structures with very limited access and since air rather than grout would be injected, the costs should be substantially lower [101,118].

5. Duration time

In geotechnical engineering, the durability of soil improvement is also important for the liquefaction mitigation of soils. Some of the methodologies presented in this review are based on new materials and concepts. Existing reports about duration time of these improvement measures for liquefaction mitigation are very limited because most of these improvement methods are still in the experimental stage. Even for the limited on site practice, the long-term in situ observation of the improved ground in the whole duration time (for decades) is difficult to implement. Here just give some examples about duration time according to laboratory tests' results.

Yegian et al. [101] conducted deep sand column tests to investigate the long-term sustainability of air entrapped in the voids of the sand. Their results found that after 442 days, the degree of saturation of the sand column only slightly increased from about 82.9–83.9% and that nearly all of this increase occurred within the first few days after the initial de-saturation. According to the results of in-situ tests by Okamura et al. [100], it was also found that the partial saturation in sandy soil may be maintained for 26 years or more. Saito et al. [80] used a series of indoor experiments to determine the long-term durability of chemical grouts. From the experimental results, it was found that the grouted sand using colloidal silica can maintain long-term durability provided with a continual inflow of ground water. Under this circumstance, the unconfined compressive strength of the grouted sand will not decrease over a curing period of 360 days, thereby demonstrating satisfactory long-term durability of colloidal silica for practical use. Delfosse-Ribay et al. [86] used the creep test to test the durability of microfine cement grouting treated soil.

As the curing time increases the liquefaction resistance will continue to increase for nanomaterials, biomaterials, chemical materials and microfine cement [114]. For the short fibers, the durability and performance of concrete reinforcement were examined, but the direct measurement of durability and aging of short fibers in soil composites is recommended. Therefore, the strength of the reinforced soil should be checked by long term, in-situ tests and continuing research are expected to verify the durability of these liquefaction mitigation measures.

6. Conclusions and recommendations

This paper reviewed recently developed methods for liquefaction mitigation based on new concepts, especially in the field of new materials used in improving liquefaction resistance of sandy soil. The review compared the recently developed methods with the traditional methods, discussing the liquefaction mitigating mechanism, effectiveness, possible executive problems and in-site application, cost and durability. In summary, these methods for liquefaction mitigation are promising and enhance our understanding of the relationship between the newly developed materials, science and technology, multidisciplinary engineering research and geotechnical engineering through innovative approaches. The relevant conclusions can be drawn as follows:

The recently developed liquefaction mitigation methods are categorized as liquefiable soil treatment with nanomaterials and synthetic fibers, backfills with recycle materials, partial soil saturation and soil improvement using biocementation, microfine cement or other grouting materials. Compared with traditional cement methods, the penetration using microfine cement, nanomaterials or the biological materials can solve the problems of great workload, operational difficulty, high cost, damage to surrounding structures and environment pollution. However, there are difficulties in the engineering practice, such as uniform penetration, gel time, gelation conditions and penetration area control. Further research is necessary to obtain a more efficient simpler method to achieve uniform penetration over large area or construction in places near existing structures. The partial saturation method can obtain effective results in laboratory tests. However, the mechanism and durability require further work and evaluation. Liquefaction mitigation using recycled materials is also an effective approach which is environment-friendly and conserves resources, but its application to engineering practice should be developed. Overall, these recently developed methods in liquefaction mitigation were shown to be effective at varying extents.

On the other hand, the majority studies of these methods are currently at the experimental stage. Although these methods have significantly improved the mechanical and dynamic properties of liquefiable soil, the on-site applications or in-situ testing of effectiveness and durability of these liquefaction mitigation methods are still relatively scarce. Therefore, the use of these methods must be verified in real site conditions. Meanwhile, as the new materials and techniques are brought into engineering use, it is important to understand their potential effects on the environment (e.g., pH, salinity, microbes, and natural organic matter) and their reactivity, mobility, bioavailability, and toxicity, to guarantee sustainable development in geotechnical engineering. However, according to the current state of the research, few researchers have studied the influence on the environment and durability that could have important impact on the engineering practice. Thus, it is important to further explore the durability of any improvement to liquefaction resistance and any environmental impact of these methods.

In summary, continued research is required to find more appropriate materials and techniques for effective liquefaction mitigation through studying the improvement mechanism, the influence on the environment and the durability of the improvement. Engineering applications should progress from the scientific experimental research stage to the commercial practice stage at low cost. Meanwhile, corresponding applied technology and industry standards need to be proposed. However, the economic and social outcomes should be improved through each new generation of new materials and techniques applied in geotechnical engineering.

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