

# The application of nanoparticles to lessen liquefaction risks: an emerging technique

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## ABSTRACT

To lessen the liquefaction risk, soil remediation could be an alternative possibility to eliminate or minimize structural damage and loss of lives during ground motion events. One of the most common approaches for limiting potential deformations of soil following the application of dynamic loads is soil densification. Traditional site stabilizing techniques have limits in terms of full-field treatment, entail extensive disturbance, and are costly to implement. Nanomaterials are being introduced for soil enhancement due to the outstanding advancement of nanotechnology. The current paper summarizes the literature, including the applications of nanoparticles in sand grain densification and future research opportunities. Nanomaterials (particularly colloidal silica, bentonite, and laponite) used in geotechnical engineering are being investigated to study how these nanoparticles improve sand reinforcement. Colloidal silica and bentonite can significantly withstand sand liquefaction due to their distinct rheological properties. Laponite, a very promising nanoparticle, can substantially enhance the liquefaction resistance of sand due to its good rheological properties and relatively small size scale. Nanoparticles have advantages in geotechnical engineering applications in terms of nanomaterial manufacturing and soil property optimization. This study reviews the application of nanoparticles to improve soil quality and comprehend the interaction between nanotechnology and geotechnical engineering by using unique approaches.

*Keywords:* Liquefaction, nanoparticles, soil densification

## 1 INTRODUCTION

The establishment and intensification of excess pore water pressure in the fully or partially saturated sand are critical to understanding and predicting liquefaction in geotechnical engineering because it influences sand shear strength and stress-strain behavior under static and cyclic loading (Yao et al. 2019). The normalized surplus pore water pressure ratio and the ratio of the number of loading cycles to the total cycles required for liquefaction have a substantial association, according to the published studies (De Alba et al., 1976; Lee and Albaisa 1974; Seed et al., 1976). In undrained cyclic loading studies on the Sacramento River and Monterey sands, Lee and Albaisa (1974) found a steady increase in excess pore water pressure as cyclic loading progressed. According to the authors, the excess pore pressure for given sand lies within a limited band that is unaffected by the sand's initial density and consolidation stress. Both field observations and laboratory research have shown that the presence of plastic particles, as well as cementation, increases the cyclic resilience of sand (Ishihara 1996; Ishihara and Koseki 1989; Saxena et al. 1988; Tokimatsu and Yoshimi 1984; Wang and Kuwano 1999). These studies demonstrate that fines have a complex behavior in sand reaction, with the quantity and types of plastic and non-plastic fines being essential. Georgiannou et al. (1991), Yamamuro and Lade (1998), Murthy et al. (2007), and Bobei et al. (2009) showed that the presence of fines alters the undrained response under static stress. Sand containing fines has been shown to have a reversible pore pressure development pattern, with increased instability at lower pre-shear effective stresses (Yamamuro and Lade 1998). During natural and artificial ground-shaking events such as explosions, blasts, and earthquakes, liquefaction

is a widespread hazard that damages constructed structures (Bray et al. 2004; Bray and Frost 2010; Cubrinovski et al. 2011). Bird and Bommer (2004) looked over fifty severe earthquakes around the world and discovered that liquefaction occurred in 62% of them, generating 15%-30% of the damage. As a result, the geotechnical community is still interested in discovering better ways to decrease liquefaction, especially around existing structures, where typical treatment approaches based on soil densification aren't always possible. As a result of urbanization and technological advancements, alternative methods and materials for lowering liquefaction risks should be researched (Huang and Wen 2015). To enhance soil strength, nanoparticle materials are being employed.

The current paper reviews the important advancements and discoveries in nanoscience research and applications in soil improvement, with a focus on liquefaction risk mitigation, as well as their implications. Yonekura and Kaga (1992), Persoff et al. (1999), and Gallagher (2000) proposed a passive site rehabilitation using nanoparticles, specifically colloidal silica, to reduce the danger of liquefaction. To demonstrate the enhancement in liquefaction resistance afforded by colloidal silica, a variety of approaches were applied, including laboratory trials, model testing, and full-scale field tests. The use of bentonite suspensions to treat liquefiable soils was examined by El Mohtar et al. (2008, 2013) and Rugg et al. (2011). These investigations look at how bentonite affects the onset of excess pore pressure at small strains, the pore pressure created at big strains under monotonic loading, and the pace of pore pressure creation during cyclic loading to liquefaction. The influence of modest percentages of laponite nanoparticles on the liquefaction resistance of sand was examined by Ochoa-Cornejo et al.

(2016) and Huang and Wang (2016). The percentages of nanoparticles-clay particles employed in their investigations ranged from 1% to 3%, which is on the low end of values investigated by other researchers like Youd et al. (2001) and below the liquefaction resistance threshold values. The preceding studies attempted to establish a way for employing nanoparticles to improve the liquefaction resistance of granular soils. The present paper primarily reviews the characteristics of various types of nanoparticles in the applications of nanoparticles in liquefaction mitigation of soil.

## 2 LIQUEFACTION

Liquefaction is a familiar phenomenon in which cyclic loading eliminates or severely reduces soil strength and stiffness. It mostly develops in loosely packed, water-logged sediments at the ground surface, which loses strength and rigidity as a result of severe ground vibration. In other words, soil liquefaction occurs when the effective stress of soil is reduced to zero or close to zero. This might happen as a result of monotonic or cyclic loading. Fully saturated loose sand can produce a significant amount of pore pressure when the load is changed, and it is the most likely to liquefy. During the undrained loading of shared and loose soil, a considerable amount of excess pore water pressure is generated as the load is transmitted from the soil skeleton to the surrounding pore water. As pore water pressure rises, effective stress diminishes, resulting in a steady loss of soil strength. Liquefaction mainly occurs in sandy or non-plastic silty soils, but it can also happen in clayey soils such as quick clay (Das and Ramana 2011; Jefferies and Been 2015).

## 3 NANOPARTICLES

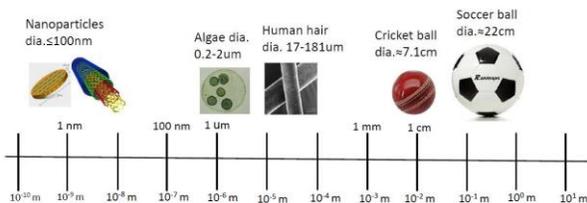


Figure 1. Scale comparison of nanoparticles dimension

Since Nobel laureate Richard P. Feynman introduced the term in his well-known 1959 lecture *There's Plenty of Room at the Bottom* (Feynman 1960), there have been numerous revolutionary developments in the field of nanotechnology. According to the European Commission's definition, at least one of the dimensions of the particle must be 100nm or less. A scale comparison of nanoparticle dimensions is shown in Figure 1. These materials can be zero, one, two, and three-dimensional nano-structural materials depending on the overall shape (Tiwari et al. 2012). Researchers revealed that the size of a substance, such as its optical capabilities, might have a significant impact on its physicochemical features. Because nanoparticles have various colors and properties that vary in size and form, they are useful in a range of fields, including bioimaging applications (Dreaden et al. 2012). There are three layers to nanoparticles: (a) surface layer, (b) shell layer, and (c)

core (Shin et al. 2016). As a result, nanotechnology can be viewed an *enabling technology* that allows existing science and technology to be extended. Nanotechnology has impacted areas as diverse as medicine, environment, energy, information and communication, and heavy industry, cutting beyond traditional discipline lines (Finch et al. 2014; Hyung et al. 2007; Peng and Lee, 2011).

## 4 LIQUEFACTION RESISTANCE USING NANOPARTICLES

The traditional stabilization approaches have a limited ability to treat the entire field, cause significant disruption, and are costly to use. As a result, new materials that can overcome the limitations must be investigated. Due to the rapid advancement of nanotechnology, nanoparticles are currently being investigated to increase sand strength qualities. However, nanotechnology applications in geotechnical engineering are a brand-new notion. There are some well-known nanoparticles namely, carbon nanotubes, colloidal silica, bentonite, and laponite, that have the potential to improve soil stability.

### 4.1 Carbon Nanotubes

Carbon Nanotubes (CNTs) are the world's strongest known substance. CNTs are cylinder-shaped molecules made up of single-layer carbon atoms wrapped up in sheets. A super-thin layer of carbon atoms structured in a hexagonal honeycomb pattern is known as graphene. CNTs are formed when graphene is rolled into a tube and are 100 times stronger than single graphene and six times lighter than steel (Chong 2003). CNTs are divided into two types: Single-Walled Carbon Nanotubes (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs). SWCNTs have a diameter of less than 1nm, while the MWCNTs have diameters of more than 100nm and are made up of numerous concentrically linked nanotubes. CNTs had an impact on the mechanical properties of clayey sand, including shear and compressive strength, according to Arabania et al. (2012). The findings show that CNTs minimize friction angle while improving cohesiveness and compressive strength in relatively small amounts. This study combined clayey sand with 0.05%–3% CNTs by weight of soil to improve the soil. The compressive strength of the soil containing 3% CNTs increased by about 120% when compared to the original clayey soil. Morsy et al. (2011) investigated the microstructure, physical characteristics, and mechanical properties of hybrid CNTs/nano-clay cement mortar composites. The addition of CNTs to nano metakaolin cement mortar increases the mortar's compressive strength by 11% (Morsy et al. 2011). As a result, even a small amount of CNTs can greatly increase the compressive strength of the soil. However, there is a growing concern that this revolutionary nanotechnology may have unintended negative repercussions for species and the environment according to several studies. CNT has the potential to induce serious human diseases (such as cancer, lung diseases, and skin diseases) and to affect the immune system (Dhawan et al. 2006). Hence, the validity and feasibility of employing CNTs as a soil reinforcing material were examined.

## 4.2 Colloidal Silica

In the liquid phase, Colloidal Silica (CS) is a suspension of small amorphous, nonporous, and generally spherical silica particles. The surface of CS in contact with water is covered in siloxane linkages ( $Si-O-Si$ ) and silanol groups ( $Si-OH$ ). As a result, CS is extremely hydrophilic and has the potential to form a large number of hydrogen bonds. Figure 2 shows the formulation of siloxane bonds and a schematic of CS particles (Spencer et al. 2008). CS is a water-based dispersion of microscope silica particles with sizes ranging from 7 to 22nm that are made from saturated silica acid solutions. CS is non-toxic, physiologically and chemically inert, and has durability properties (Chang et al. 1994). According to Chapa-Gonzalez et al. (2018), CS is commonly made in a multi-step process that involves partially neutralizing an alkali-silicate solution and creating silica nuclei. The size of the subunits in CS particles is typically 1 to 5nm.

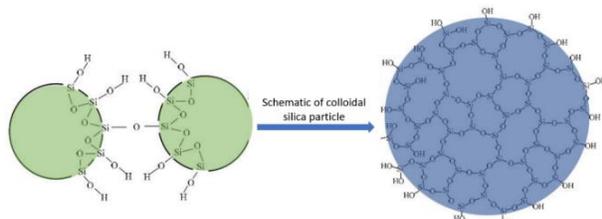


Figure 2. Formulation of siloxane bonds and a schematic of colloidal silica particle, after Spencer et al. (2008)

Yonekura and Kaga (1992) proposed CS as a substitute for sodium silicate, the most extensively used chemical grout. Persoff et al. (1999) investigated how the concentration of CS in sand affects its strength and hydraulic conductivity. Unconfined compressive strengths of 158 and 317kPa were found in sand specimens stabilized with 10% and 20% CS (by weight), respectively, demonstrating a direct relationship between gain strength and CS concentration. Gallagher (2000) proposed passive site remediation with CS to reduce liquefaction risk and enhance liquefaction resistance, as evidenced by laboratory research, model testing, and full-scale field tests. Gallagher and Mitchell (2002) found that the unconfined compressive strength baseline of samples treated with 5%–20% CS varied from 32 to 222kPa. Gallagher et al. (2002) examined the efficacy of CS treatment in improving liquefaction resistance and reducing the deformation of loose sands using centrifuge modeling. Gallagher and Koch (2003) published the results of box model studies using low-head injection wells to apply CS to loose sands. In this paper, centrifuge modeling is used to investigate the effects of CS treatment on the liquefaction and deformation parameters of loose, liquefiable sands during centrifuge in-flight shaking. Agapoulaki and Papadimitriou (2018) reported a set of viscosity measurements of various CS solutions, which corroborated prior findings in the literature and indicated temperature as a new governing parameter. A reliable statistical analysis can be carried out due to a large number of measurements, resulting in the creation of a set of charts and equations for calculating the time-increasing viscosity of CS solutions. Gallagher (2000) and Gallagher and

Mitchell (2002) studied the rheology of CS by conducting extensive viscosity measurement tests on three different types of CS with varying particle sizes at various pH values and salt concentrations and found that these are important parameters affecting the gelation process. These studies also suggested that before injecting CS into the ground in situ, case-specific viscosity measurement tests be taken which would necessitate specialist equipment and experience. As a result, a reliable method for computing the viscosity-versus-time curve of CS solutions with known parameters such as silica type, CS and cation content,  $pH$ , and temperature would be extremely beneficial.

## 4.3 Bentonite

Bentonite is a water-absorbent swelling clay formed mostly of montmorillonite, an aluminum phyllosilicate mineral. When volcanic ash is weathered in seawater, volcanic glass in the ash is transformed into clay minerals, yielding a processed clay mineral (Darvishi and Morsali 2011; Nesse 2000; Sutherland 2014). Freshly exposed bentonite beds are white or pale blue or green, changing to a cream tint, then depending on the exposure ages the color becomes yellow, red, or brown (Jackson 1997). When nano bentonite dissolves in water, it forms gelatinous or suspended solutions with high viscosity, thixotropy, and lubricity (Teplitkiy et al. 2005). Bentonite is made of the aluminum phyllosilicate mineral montmorillonite, which has a low-charge TOT-crystal structure. Two T-sheets are connected to each other on either side of an O-sheet in each layer of a montmorillonite crystal. The name T-sheets comes from the fact that each aluminum or silicon ion in the sheet is surrounded by four oxygen ions organized in a tetrahedron. The O-sheets get their name from the fact that each aluminum ion is surrounded by six oxygen or hydroxyl ions in an octahedron shape. Figure 3 represents the structural formula of bentonite (Perry, 2019). There are commonly two types of bentonites used in several industries: sodium bentonite and calcium bentonite. Sodium bentonite is more valuable than calcium bentonite (Brown et al. 2016).

- *Sodium bentonite*: When wet, sodium bentonite swells and absorbs up to several times its dry mass in water. It is widely used in drilling mud for oil and gas wells, as well as boreholes for geotechnical investigations, due to its exceptional colloidal qualities (Hosterman and Patterson, 1992). Sodium bentonite is also effective as a sealant, as it creates a self-sealing, low permeability barrier. Bentonite is also used as the backfill material in waste containment projects (Butcher 1993). In geo-environmental applications such as the addition of polymers, numerous surface alterations to sodium bentonite increase some rheological or sealing behaviors (Theng 1979). As fertilizer prills, sodium bentonite can be mixed with sulfur, which allows for slower sulfur oxidation to sulfate, an important plant nutrient, and keeps sulfate levels in rainfall-leached soil for longer than pure powdered sulfur or gypsum (Boswell et al. 1988). Organic farming has used sulfur/bentonite pads with organic fertilizers applied (Muscolo et al. 2020).
- *Calcium bentonite*: Calcium bentonite is a beneficial adsorbent of ions in solution. It is the key element of

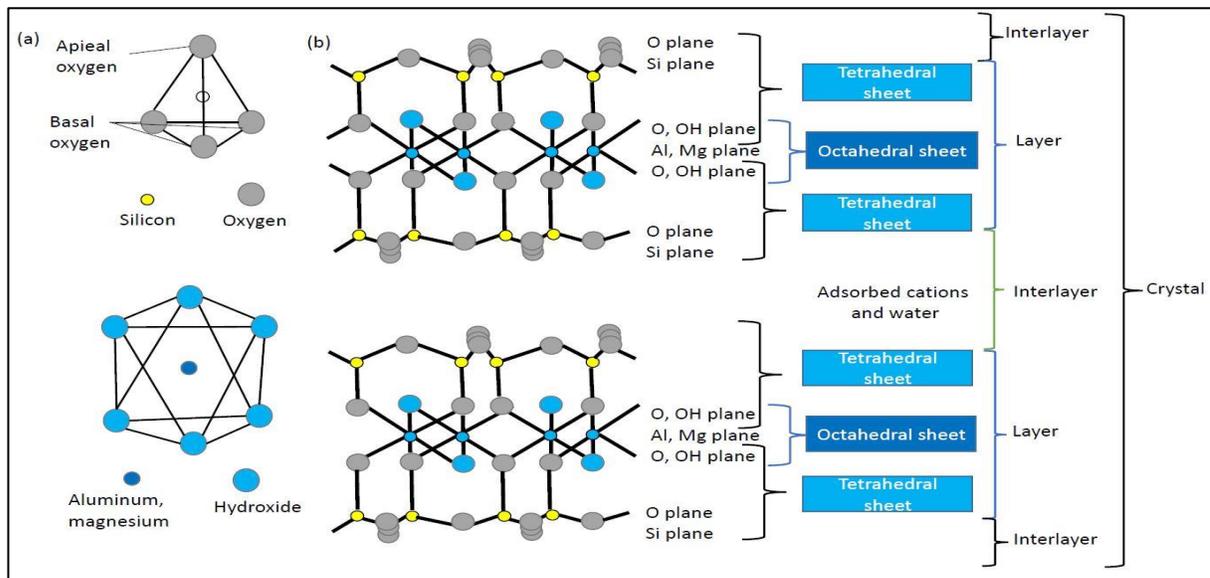


Figure 3. The structural formula of bentonite, after Perry (2019)

fuller's earth and one of the first industrial cleaning agents (Robertson 1986). By using an ion-exchange technique, calcium bentonite can be transformed into sodium bentonite. This usually entails adding 5-10% of soluble sodium salt, such as sodium carbonate, to wet bentonite, mixing thoroughly, and allowing time for ion exchange and water to remove the calcium exchanged (Christidis et al. 2006, Eisenhour and Brown 2009).

- **Potassium bentonite:** Potassium bentonite, also known as potash bentonite or K-bentonite, is a potassium-rich illicit clay generated by the alteration of smectic clay (McCarty et al. 2009). Illite is a high-charge TOT clay mineral in which sheets are strongly bound by more potassium ions, making it a non-swelling clay with limited industrial applications (Nesse 2000).

Drilling fluids containing bentonite dispersions are commonly utilized for excavation support, grouting, and impermeable barriers. The rheological properties of Bentonite dispersions must be controlled in order for them to be successful in various applications. The rheology of bentonite dispersions is affected by several factors including clay content,  $p^H$ , water ionic strength, and kind of cation and anion (Durn et al. 2000; Harvey and Lagaly 2013; Kelessidis et al. 2007; Laribi et al. 2006; Malfoy et al. 2003; Penner and Lagaly 2001, Tombacz and Szekeres 2004). Bentonite exists in a variety of states as a result of changes in these constraints including repulsive gel, attractive gel, and sediment (Abend and Lagaly 2000; Lagaly and Dekany 2013; Michot et al. 2004). When it comes to the influence of plastic fines on liquefaction resistance, the general consensus is that their presence increases it. Field observations and laboratory evidence backed up these ground-breaking findings. Gratchev et al. (2006) used a ring-shear apparatus to investigate the liquefaction of clayey soils. They used bentonite-sand mixes and natural clayey soils recovered from the sliding

surfaces of earthquake-induced landslides. A small amount of bentonite (7%) induces rapid liquefaction, whereas an increase in bentonite content (11%) significantly increased liquefaction resistance. The liquefaction resistance of bentonite-sand mixtures was found to be significantly higher than that of kaolin and illite-sand mixtures. Plasticity has a significant impact on liquefaction resistance according to the findings. A scanning electron microscope was used to examine the microfabric of clayey soil, revealing that the soil's liquefaction potential was linked to specific particle configurations. Clarke (2008) and El Mohtar et al. (2008) conducted extensive experiments on this approach. The study had two goals: (a) to evaluate the properties of bentonite slurry, and (b) to look into the efficacy of bentonite treatment. Clarke (2008) looked into the rheological properties of bentonite slurry to see if it could infiltrate the soil matrix and how long the pore fluid would take to gel. El Mohtar et al. (2008) investigated the mechanical properties of bentonite-treated sand, as well as its efficacy in preventing liquefaction. For a given cyclic stress ratio, bentonite treatment increases the number of loading cycles that a sand sample can withstand before liquefaction under undrained cyclic triaxial conditions. Bentonite appears to extend the elastic zone of material behavior over a wide range of strain values. Clarke (2008) discovered that this happens with bentonite as well, albeit at much lower concentrations. The at-rest and flow properties of concentrated (10% clay by the total mass of dispersion) bentonite dispersions produced with SPP were investigated in rheological testing (0 to 2% percent by mass of bentonite). These tests were carried out from the time the ingredients were blended until they were matured for around two years. The tests used a rheometer to get rheological data that is directly related to bentonite dispersion performance. Witthoef et al. (2012) verified bentonite suspension liquefaction mitigation and control effect at the field scale by using the finite difference method FLAC and demonstrated the extent of reinforcement.

#### 4.4 Laponite



Figure 4. Laponite powder

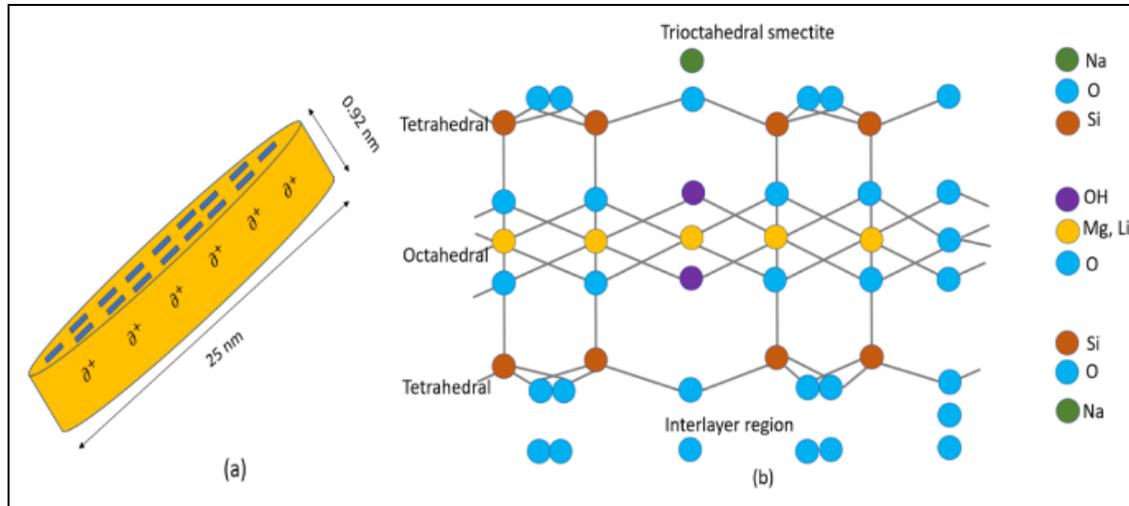


Figure 5: (a) Geometry of individual laponite particles, and (b) Idealized structural formula of laponite, after BYK Additives and Instruments (2014)

Laponite is a multilayer silicate nanoparticle made from inorganic mineral sources that are created synthetically. In its dry state, laponite is a fine white powder (Figure 4). It is almost 10 times smaller than bentonite with a thickness of 1 nm and a width of 25 nm. Figure 5(a) shows the geometry of individual laponite particles (BYK 2014). Figure 5(b) represents the idealized structural formula of laponite. Its chemical composition is 65.82%  $SiO_2$ , 30.15%  $MgO$ , 3.20%  $Na_2O$  and 0.83%  $Li_2O$  corresponding to the general formula as follows:  $Na^{+0.7}[Si_8Mg_{5.5}Li_{0.3}H_4O_{24}]^{-0.7}$  (El-Howayek 2011; Paula et al. 2009). It disperses quickly in water, forming disc sheet-shaped grain structures, resulting in a colorless and transparent solution. The surface discharges a considerable number of negative charges because a lithium-ion valence substitutes some of the bivalent magnesium ions on the particle surface. Protonation of hydroxides on the periphery, such as Mg-OH and S-OH, requires a little amount of positive charge. Laponite is insoluble in water, and some of the suspended material settles after a while, causing the liquid to evaporate (Levitz et al. 2000). Laponite is used to boost the value of a variety of industrial and consumer products by increasing their performance and attributes.

Ochoa-Cornejo et al. (2016) and Huang and Wang (2016) conducted new research on the use of laponite to reduce liquefaction risk. The findings revealed new information on the effects of high plasticity on sand cyclic response as well as the extreme effects of high plastic

particles. These findings are intriguing in view of the authors' hypothesis that laponite could be used to minimize liquefaction. Ochoa-Cornejo et al. (2016) investigated the influence of 1%–5% laponite by dry mass of sand with a flexibility index larger than 1000% on the cyclic response of sand with relative density in the 15%–25% range. The study is based on cyclic triaxial tests performed on dry-pluviated specimens that were later saturated with water. One percent laponite has an effect on all stages of cyclic testing, from the first response to liquefaction, increasing cyclic resistance. More benefits can be demonstrated with a longer pre-shear aging time or greater laponite dosages

(3%–5%). The behavior is owing to decreased sand particle mobility under cyclic loading, which can be described by two mechanisms: (a) particle contact bonding/bridging caused by charged laponite fines attracted to the sand grains and (b) creation of a pore fluid with solid-like characteristics. To avoid liquefaction, Huang and Wang (2016) also recommended using laponite with liquefiable silty sand. The study also observed a mixture of laponite with sand. Dynamic triaxial testing was used to examine the cyclic behavior and liquefaction resistance of laponite-sand specimens. To evaluate the efficacy of laponite in liquefaction reduction, the pore pressure accumulation process and deformation characteristics of untreated sand and laponite-sand specimens were investigated. In order to identify the appropriate gel time for laponite-sand specimens, the viscosity of laponite suspensions was also examined. The rheological parameters of laponite suspension were determined using rheology experiments, and the microstructure of laponite-silty sand mixes was examined using scanning electron microscopy. This study provided experimental evidence of mixing laponite with sand on liquefaction susceptibility reduction in the saturated condition same as Ochoa-Cornejo et al. (2016). Dynamic triaxial tests were used to examine the cyclic behavior and liquefaction resistance of laponite-sand specimens. Huang et al. (2021) evaluated the effects of laponite in high-performance water-based drilling fluids on shale inhibition, plugging, and lubrication.

The linear swelling test and the shale recovery test were used to assess the shale inhibition performance. Nitrogen adsorption experiments and scanning electron microscope observations were performed to assess plugging performance. An extreme pressure lubricity test was used to evaluate the lubricating property. Experiments have shown that laponite inhibits shale formation better than traditional shale inhibitors, such as polyamine and *KCl*. By dramatically reducing the surface area and pore volume, laponite can successfully plug shale pores. It can also minimize shale porosity and produce a smooth nanofilm according to scanning electron microscope data. By improving the smoothness of the drill pipes/wellbore interface and isolating direct contact between the wellbore and the drill string, laponite helps to increase the drilling fluid's lubricating properties. The performance of laponite is largely attributable to its disk-like nanostructure and charged surfaces.

## 5 CONCLUSION

The current study highlights the findings of four well-known nanoparticles that have the ability to reduce liquefaction risks by enhancing the soil's compressive strength under cyclic loadings. CS is a low-cost nanomaterial that can be transformed into a gel-like solid and has been found to resist liquefaction. This paper examines the application of CS for ground improvement and liquefaction mitigation. The primary factors that can have a significant impact on CS transportation and strengthening effect are thoroughly examined. According to the previous literature, the two essential criteria that affect the ground improvement effects are the CS concentration and cure time. However, management of the gelling duration, CS injection success rate, and CS distribution with minimal deposition remain problems for this CS-based soil liquefaction mitigation approach. Another well-known nanoparticle is nanobentonite, a processed clay mineral generated by weathering volcanic ash. Bentonite is a chemically and biologically inert mineral. Bentonite forms gelatinous or suspended solutions in aqueous media due to its high viscosity, thixotropy, and lubricity. As a result, bentonite has been utilized as a drilling fluid additive to improve the characteristics of drilling mud and reduce fluid loss to the rock formation. According to the studied articles, only 10% bentonite can generate thixotropy gel to lessen the risk of liquefaction. The most significant disadvantage of bentonite is that particle penetration of bentonite suspensions in the sand might be difficult. According to several published studies, adding 0.5%-2% sodium pyrophosphate to bentonite solutions can minimize early yield stress and viscosity. Laponite is a new promising nanoparticle that is temperature insensitive and physiologically and chemically inert. Experiments have demonstrated that adding a trace quantity of laponite to sand can significantly reduce the formation of excess pore pressure during cyclic loadings. When laponite dissolves in water, it may undergo a fluid-solid transition, resulting in a transparent, solid-like gel that can be used as a soil thickening agent. Despite the fact that laponite's thixotropy allows it to increase its pore pressure, liquefaction can still occur. The initiation of liquefaction is substantially slower than in clean sand specimens under the same loading

conditions because pore pressure generation is greatly delayed.

To further examine soil improvement employing nanoparticles, systemic research methodologies encompassing nanomaterial science and geotechnical engineering approaches should be developed. More research is needed to check if soil-nanoparticle homogeneity can be maintained in the targeted area. Another essential consideration is whether the requisite concentrated nanoparticles can travel the necessary distance; in other words, whether nanoparticles will become gel before reaching their intended destination. Nanoparticle characterization, chemical composition, microstructure, and nanoparticle-soil medium interface interaction are all important aspects in determining nanoparticle performance and application in real-world circumstances. There is a need for more research into the material properties of nanoparticles that can be used to improve soil qualities.

## 6 COMPETING INTERESTS STATEMENTS

The authors have no relevant financial or non-financial interests to disclose.

## 7 FUNDING STATEMENTS

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