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## Undrained behavior of laponite-treated specimens

G.S. Pardo & R.P. Orense

*University of Auckland, Auckland, New Zealand*

**ABSTRACT:** Nano-materials have been introduced as an innovative solution in many industrial applications. Laponite is a synthetic nano-clay that can modify the behavior of any fluid in which it is dispersed. This study focuses on the effect of adding 1% laponite on the undrained strength of loose saturated sand. Cyclic simple shear tests confirm the strain rate-dependency of laponite suspensions. Thus, tests performed at lower cyclic stress ratio show considerably higher liquefaction resistance when compared to untreated sand specimens. Laponite's ability to recover is assessed by subjecting the treated samples to a series of three cyclic loading phases. These specimens require up to 100 times more cycles to liquefy compared to untreated sand specimens with similar density. However, monotonic undrained tests show that laponite has a lubricating effect, reducing friction between particles as well as the overall bearing capacity of the soil.

### 1 INTRODUCTION

The problem of interest of this study is soil liquefaction, a phenomenon in which loose saturated sand loses its strength and stiffness due to an increase in the excess of pore water pressure as a result of shaking. With every big earthquake, soil liquefaction has been observed to occur close to rivers, lakes and other water bodies, and it is usually accompanied by large ground deformations, sand boils, and lateral spreading. Some traditional liquefaction countermeasure techniques have performed well in past earthquakes, but liquefaction is still happening, and some of these techniques are difficult to implement in highly populated areas.

Nano-materials have been introduced as an innovative solution in many industrial applications. As these materials are so small, they have a high specific surface area, and their contacts are governed by electrostatic forces which give them unique properties when they interact with other materials. Some of the nano-materials being used for remediation purposes are colloidal silica, bentonite and laponite. In passive site remediation, colloidal silica has been used to provide cementation which can restrain shear strain development (Gallagher 2000, Gallagher et al. 2007). Results from cyclic triaxial tests (Gallagher & Mitchell 2002), resonant column tests (Spencer et al. 2007) and centrifuge model tests (Conlee et al. 2012) indicated that colloidal silica could be injected into a clean sand deposit and increase its shear modulus and reduce shear strain. On the other hand, laponite and bentonite are nano-clays that can modify the pore fluid (e.g. Rugg et al., 2011; El Mohtar et al., 2013; Santagata et al., 2015; Ochoa-Cornejo et al., 2016); these nano-clays transform the water rheology into a solid-like fluid, delaying the generation of excess pore water pressure when subjected to earthquake shaking.

Laponite is a synthetic nano-clay with a chemical composition similar to those of naturally occurring smectite clays. It has a maximum particle size of 100 nm, which is one order of magnitude smaller than other smectite clays, such as bentonite or hectorite (BYK Additives & Instruments 2014).

One of the primary uses of laponite is as rheology modifier because it can modify the behavior of many fluids in which it is dispersed, such as toothpaste or drilling fluids (Huang et al. 2018, Mayes 1979, Sandvold 2012). Laponite is highly plastic, and there is a general agreement that the addition of highly plastic fines in sand increases the sand's liquefaction resistance (Ishihara & Koseki 1989, Koseki et al. 1986). These properties have brought attention to laponite as an innovative alternative to mitigate soil liquefaction.

When dispersed in water, laponite transforms water into a gel with thixotropic properties. This behavior is related to the flat-disc shape of its crystals (Figure 1a) and its chemical structure that naturally causes its surface to have a negative charge and its edges to have a positive charge (Barnes 1997). This makes its particles to conglomerate and form an aggregate of silt/clay size. When the dry particles are added to water, they disperse and re-arrange themselves in a kind of house-of-cards formation (Figure 1b) such that at the beginning they form a Newtonian (low-viscosity) fluid with viscosity similar to water and they could be injected into the groundwater without the need for compaction. With time, this formation hardens and becomes a gel with yielding shear stress,  $\tau_{y,s}$ , which means that for a shear stress lower than this threshold, the gel behaves like an elastic solid, and when the shear stress is higher than the yield stress, i.e.  $\tau \geq \tau_{y,s}$ , the network breaks and the material flows with decreasing viscosity (Figure 1c). When the shear stress is removed, the gel goes back to rest and the structure begins to recover; with hardening, the shear modulus continues to increase as time passes and its viscosity increases again (Barnes 1997). This characteristic suggests that laponite could be used as a suitable method to mitigate soil liquefaction because it could self-recover and resist new cyclic shear stress episode.

Its injectability has been studied on a uniform sand (Mele et al. 2018) and it was found that in order to inject a suspension with a concentration higher than 3% by weight of water, it is necessary to use an additive (sodium pyrophosphate).

Studies on the rheology of the suspension concluded that 72 hours are enough for the suspension to strengthen and develop enough shear modulus (El Howayek 2011). In the same study, the author compared Cryo-SEM images of specimens prepared with two different methods, i.e. by dry-mixing and by injection; he concluded that dry-mixing method produced non-uniform specimens, with some air pockets in-between the particles.

Regarding laponite's potential to mitigate soil liquefaction, Ochoa-Cornejo et al. (2014, 2016) studied through cyclic triaxial tests the effect of adding 1% laponite powder into clean Ottawa sand and found an increase in the number of cycles to reach liquefaction, from about 100 to 600 for similar shear stress. Huang et al. (2018) also performed cyclic triaxial tests and compared different treatments of laponite (0%, 2%, 2.5%, 3%, 3.5% by weight of sand) and different ageing times (2, 4, 6 days) and obtained an increased liquefaction resistance with the addition of laponite and with the passage of time. However, they also prepared the specimen by dry-mixing, which involves a different mechanism than injecting the suspension into the soil deposit. Rheological dynamic oscillatory measurements indicated that a suspension with 3.25% laponite had similar dynamic properties to that of a suspension with 10% bentonite (Santagata et al. 2015). In addition, resonant column tests on specimens permeated with laponite suspension with a concentration in water of 3.25% w/w (equivalent to 1% by weight of sand) after 72 hours showed slightly less reduction in shear modulus compared with pure sand specimen with a relative density of 22% (Santagata et al. 2015).

The use of laponite as a possible alternative to mitigate soil liquefaction is still in evaluation stage, and more research is still needed to define its applicability for this purpose. Additionally, it is necessary to assess its other geotechnical properties, such as its effect on the static response of the host sand.

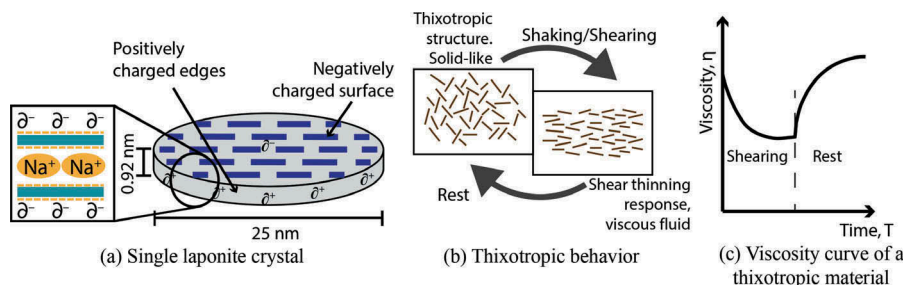


Figure 1. Schematic showing laponite thixotropy

The study presented in this paper focuses on the effect of adding 1% laponite on the undrained resistance of loose saturated sand. For this purpose, both cyclic and monotonic tests were performed. Additionally, the self-healing capacity of this material was assessed by subjecting the treated specimens to a series of three cyclic loading phases.

## 2 MATERIALS AND METHODOLOGY

### 2.1 Materials

The host sand is a river sand, sourced from the Waikato River in New Zealand, and referred locally as Mercer River sand. It has a uniform distribution and no fines content (Figure 2). Its average particle size is 0.81 mm, and its principal index properties are listed in Table 1.

Laponite is a synthetic nano-clay with chemical composition analogous to that of naturally occurring clays. It has disk shape of 1 nm thickness, and 25 nm diameter (Figure 3a), and its chemical structural formula  $(\text{Na}^{+0.7}[(\text{Si}_8\text{Mg}_{5.5}\text{Li}_{0.3})\text{O}_{20}(\text{OH})_4])^{-0.7}$  is represented in Figure 3b. The specific gravity reported by El Howayek (2011) is  $G_s = 2.57$ .

The laponite grade used in this study is RD (for rapid dispersion), manufactured by BYK Additives. This grade is a general-purpose rheology modifier that changes the way in which the dispersing fluid deforms when shear stress is applied. When laponite powder (Figure 3c) is just added to water, it forms a transparent, non-toxic fluid (Figure 3d).

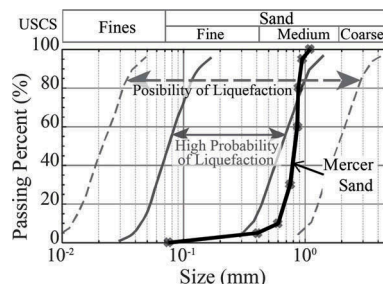


Figure 2. Grain size distribution curve of Mercer sand, with boundaries showing probability of liquefaction (after Tsuchida, 1970)

Table 1. Basic index properties of Mercer river sand.

Grain size	distribution properties	Index	properties
$C_U$	2.93	$G_s$	2.65
$D_{10}$	0.31 mm	$e_{\min}$	0.630
$D_{50}$	0.81 mm	$e_{\max}$	0.849
$D_{60}$	0.90 mm	$D_r$	29%

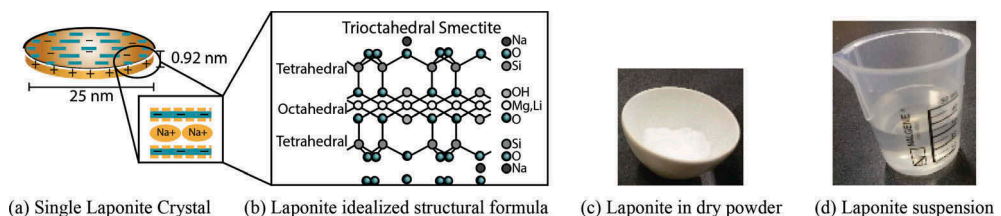


Figure 3. Characteristics of laponite

## 2.2 Sample preparation method

There are several methods adopted to prepare reconstituted soil specimens. In this study, the modified slurry deposition method was selected (Ishihara et al. 1978, Khalili & Wijewickreme 2008) because this method can be used to prepare highly gap-graded specimen that is already saturated from the beginning. Figure 4 shows a schematic of the preparation method used. The method was first assessed in only pure sand specimens, and it was found that it was possible to reproduce specimens of constant void ratio,  $e = 0.758$  (i.e., relative density  $D_r = 29\%$ ) with less than  $\pm 2\%$  variation. To prepare laponite-treated specimens, the sand skeleton density was kept constant. The amount of water to have 100% saturation was first computed based on the target void ratio; thus, the concentration of laponite by weight of water had to be 3.4% in order to have a treatment of 1% laponite by weight of sand. Therefore, laponite suspension was prepared by pouring 3.4% laponite powder into the vortex of deaired water being stirred. Then, the suspension was added to the dry sand, and the mixture was stirred manually until a uniform paste was obtained (Figure 4a). This mixture was deposited in the mold with a spoon (Figure 4b). Finally, the specimen was levelled and sealed inside the simple shear test mold ready to be tested (Figure 4d).

## 2.3 Simple shear tests

In the simple shear test, a cylindrical specimen of 63 mm diameter and 24 mm height was confined by a rigid stack of rings made of Teflon (Figure 4b). The rings kept the cross-sectional area of the specimen constant by not allowing radial extension to occur during the whole test. The top cap of the specimen was locked in the horizontal direction, but it could move in the vertical direction. The bottom of the base was mobile in the horizontal direction only, so shearing can be applied either by displacement-control or by force-control, allowing the specimen to undergo simple shear mode of deformation (Figure 4d).

The first stage of each test was consolidation, where the specimen was loaded vertically under  $K_0$  conditions. Water can drain from the specimen vertically towards the top or bottom porous stones. The change in vertical displacement was recorded while keeping the vertical stress constant. The next step was shearing, which was done either monotonically or cyclically in undrained condition. The undrained condition was simulated by keeping the volume of the specimen constant. Thus, the vertical load had to be automatically adjusted in order to keep the specimen height constant. Studies have compared this principle with the truly undrained conditions, and the responses have been reported to be identical (Dyvik et al. 1987).

For cyclic tests, the treated specimens were tested in three phases, as described in Figure 4c. In Phase 1, the samples were consolidated with a vertical load of  $\sigma'_{v0} = 100$  kPa for 72 hours. Next, cyclic shear loading was applied at specified cyclic shear stress ratios ( $CSR = \tau/\sigma'_{v0}$ ). Liquefaction resistance was defined in terms of deformation, i.e. the number of cycles required for the specimen to reach a double amplitude shear strain of 7.5%. After the specimens liquefied, they were allowed to rest for an additional 72 hours before shearing them again in Phases 2 and 3. It was expected that if the same specimen was subjected to a series of cyclic loading

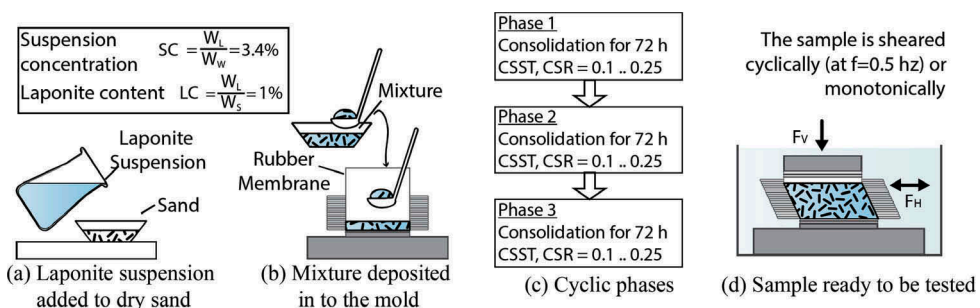


Figure 4. Sample preparation method for simple shear test specimens

phases, it would densify so that the improvement in the behavior would be due to a combination of the recovery and hardening of the laponite suspension plus the reduction in the void ratio. In order to remove the effect of densification of the specimen, another set of pure sand specimens were prepared to have void ratio after consolidation similar to those with laponite-treated specimen pre-shearing.

Monotonic undrained tests were performed at confining pressures  $\sigma'_{v0} = 100$  kPa, 200 kPa, and 300 kPa. In these tests, laponite-treated specimens were consolidated for 72 hours before being sheared at constant volume, while pure sand specimen were consolidated for about 2 – 3 hours.

### 3 RESULTS

#### 3.1 Results of cyclic simple shear tests

Figure 5 shows the results from cyclic simple shear tests at different *CSR*. In the figure, the colors of the marker fill are proportional to the void ratio after consolidation ( $e_c$  in the legend of the figure). Different comparisons are made: in Figure 5a, pure sand is contrasted with the three phases of shearing performed on laponite-treated specimens; in Figure 5b, only the results for pure sand specimens are plotted to compare samples with different  $e_c$  (these specimens had similar post-consolidation void ratio to the ones measured in laponite-treated specimens in phases 1, 2 and 3); and Figures 5c, 5d and 5e show the results for laponite-treated specimens in Phases 1, 2 and 3 of cyclic shear, respectively, compared with those of pure sand specimens with similar  $e_c$ .

When comparing just Phase 1 (Figure 5c), laponite-treated specimens has higher liquefaction resistance only for lower *CSR*, where it requires about 100 times more cycles than the non-treated specimens for it to liquefy. However, at higher *CSR*, the resistance was more or less similar to those of pure-sand specimens.

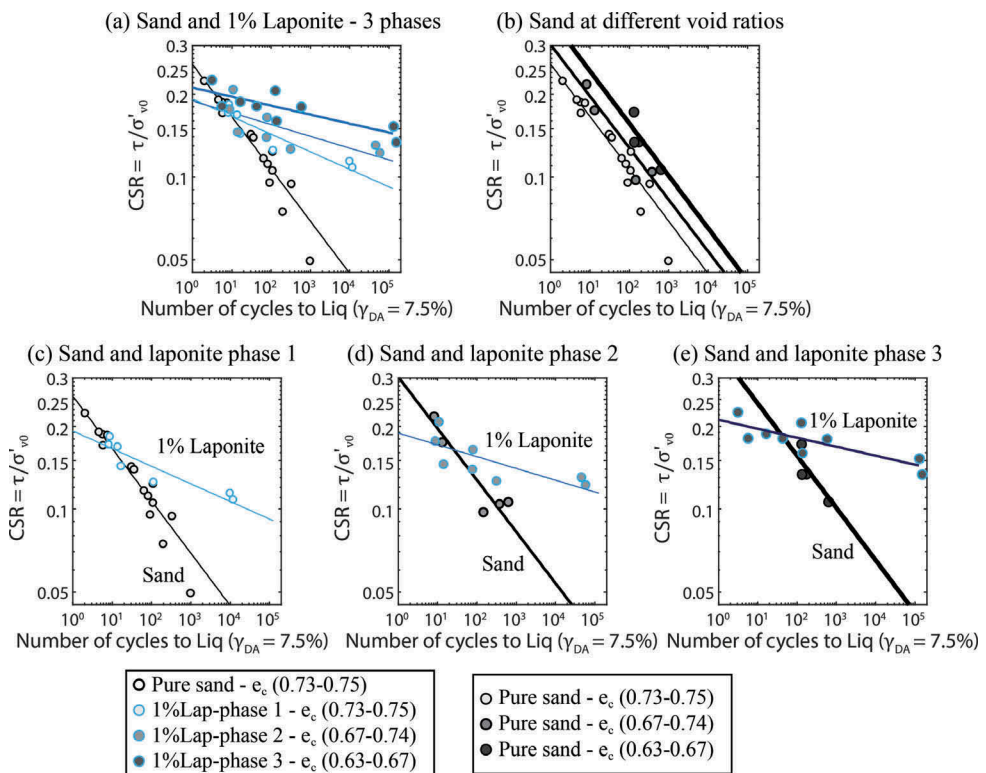


Figure 5. Results of undrained cyclic simple shear tests



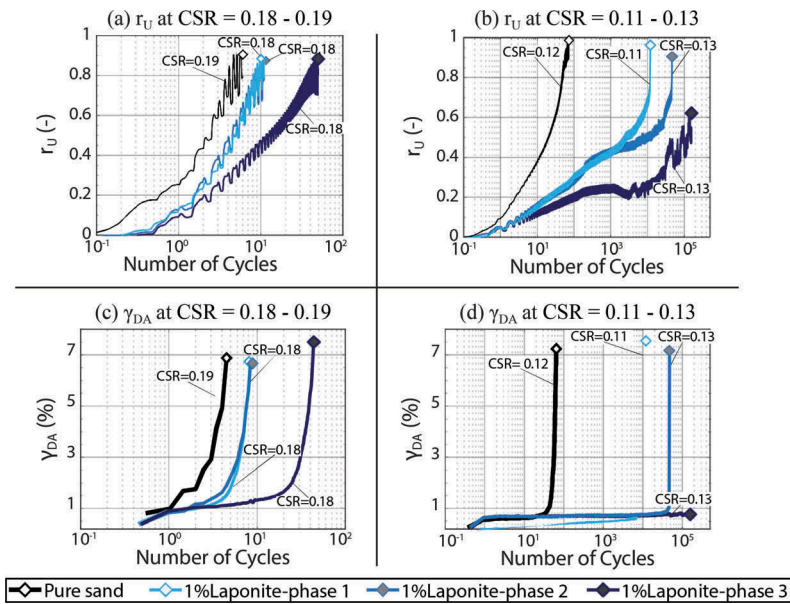


Figure 6. Comparison of development of the excess of pore water pressure and double amplitude shear strain at  $CSR = 0.11 - 0.13$  and  $CSR = 0.18 - 0.19$

Based on laponite rheology, it was expected that after the cyclic loading was ceased, laponite would recover itself. Thus, in Phases 2 and 3, laponite had 72 hours to recover before the cyclic load was re-applied and a trend similar to Phase 1 was observed (see Figures 5d and 5e). Thus, at lower  $CSR$ , the resistance to liquefaction increased by two orders of magnitude when compared with those of pure sand specimens of similar void ratios after consolidation. However, for higher  $CSR$ , the resistance was similar to that without treatment.

Figure 6 shows the comparison between the control case (pure sand with  $e_c$  between 0.73 and 0.75) and laponite-treated sand at three different phases, with  $CSR = 0.11 - 0.13$  and  $CSR = 0.18 - 0.19$ . The upper graphs compare the development of excess of pore water pressure ratio,  $r_u$ , while the lower plots compare the accumulation of double amplitude shear strain,  $\gamma_{DA}$ . The samples treated with laponite showed delayed generation of excess of pore water pressure and less shear strain development with number of cycles, especially at lower  $CSR$ . For example, at  $CSR = 0.13$ , the specimen with 1% laponite did not reach liquefaction in Phase 3, even after  $10^5$  cycles.

When laponite-treated specimens are compared with pure sand specimen with similar void ratios, it is clear that the mechanism of improvement is not due to the densification occurring post-cyclic shearing. It is more likely to be due to the recovery and the continuous hardening of laponite suspensions. Additionally, the specimen subjected to lower  $CSR = 0.11 - 0.13$  seems to recover while the tests was still in progress (see Figure 6b). The specimen underwent more than  $10^5$  cycles without developing much deformation ( $\gamma_{DA} < 1\%$ ), and the excess pore water pressure oscillated more at the end of the test, indicating that the sample was recovering its strength while the test was in progress.

### 3.2 Results of monotonic undrained simple shear tests

Results of monotonic undrained tests are presented in Figure 7. Under monotonic loading, laponite-treated specimens seem not to perform so well. Laponite had a lubricating effect, reducing the internal friction angle from  $30^\circ$  to  $20^\circ$ , but increasing the cohesion from 0 kPa to 15 kPa (Figure 7a). Overall, however, the shear strength of the laponite-treated specimen was reduced close to half of the pure-sand specimen (Figure 7b); in terms of the development of excess of pore water pressure, both types of specimens initially showed similar contractive response, but with continuous shearing, the treated specimens were less dilative (Figure 7c).

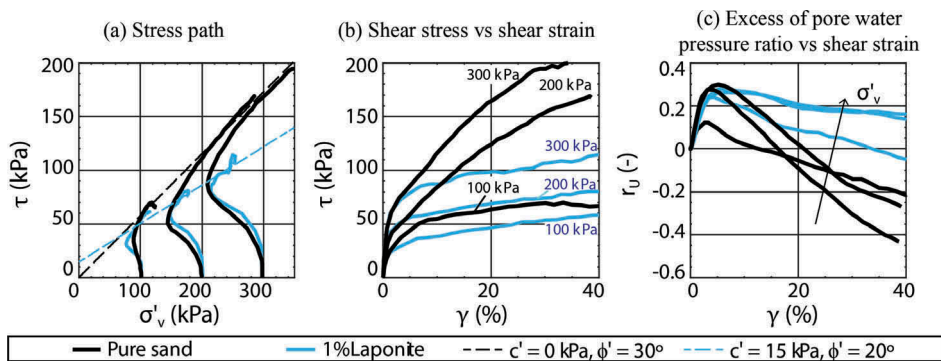


Figure 7. Results of monotonic undrained simple shear tests

#### 4 DISCUSSION AND CONCLUSIONS

This paper presented the results of the undrained monotonic and cyclic simple shear tests conducted on laponite-treated specimens. The main objectives of the study were: (i) to evaluate the effect of laponite on the liquefaction resistance of sand; (ii) to evaluate the effect of self-healing characteristic of laponite on the cyclic resistance of sand; and (iii) to assess the effect of laponite on the undrained monotonic strength of the host sand. Unlike other studies on liquefaction resistance, in this investigation, laponite in suspension was added instead of dry-mixing the soil with laponite powder. It is believed that by preparing the laponite suspension, the pore water is completely modified, and the rheology of laponite is more representative of how it would behave in real-field applications.

Laponite recovery characteristics were assessed using a cyclic simple shear apparatus, in which the same sample was subjected to three phases of consolidation and cyclic shear application. Even though the void ratio of the samples decreased after each phase, when compared with pure sand samples with similar  $e_c$ , a considerable increase in the number of cycles to reach liquefaction was monitored. Therefore, the samples not only recovered, but also endured even more cycles because the laponite suspension continued to harden with time. These results indicated that with only 1% laponite by weight of sand, it is possible to considerably increase the liquefaction resistance; if an aftershock comes, the treatment may be able to resist it. However, given the thinning behavior of laponite suspensions (i.e. decrease in viscosity with increase in shear), such effectiveness observed when  $CSR = 0.11$  became minor for higher  $CSR = 0.18$ .

On the other hand, the results of undrained monotonic simple shear tests indicated that adding 1% laponite to sand resulted in a decrease in the friction angle that was not compensated by an appropriate increase in cohesion, resulting in reduced overall strength of the soil in static condition.

The mechanism of improvement is related to the transformation of pore water into a non-Newtonian fluid; this change in rheology is reflected in the delayed development of excess pore pressure and in the recovery of the specimen after each cyclic shearing phase. Moreover, it is also manifested in the reduction of friction angle in static conditions.

Laponite is currently in preliminary stages of investigation as a soil stabilizer, and the results presented in this paper confirmed its potential for soil liquefaction mitigation, because it delayed the development in pore water pressure and restrained the accumulation of shear strain.

In practical applications, laponite could be injected or delivered into the groundwater flow, as in passive remediation, without the need for compaction. It would be recommended to inject laponite only to a depth where the soil is expected to lose its effective stress due to the increase in pore water pressure. Consequently, the reduction in friction angle would not affect the whole soil deposit.



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