

## Geotechnical Properties of Laponite -Treated Sands in Reliquefaction Events

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### ABSTRACT :

Laponite is a nanomaterial that can change the way of behaving of the liquid wherein it is scattered, changing it into a non-Newtonian liquid with starting low consistency that solidifies with time. Also, since the gel recuperates after shear pressure has been taken out, it has strong properties. In this review, a few series of lab component testing, for example, oedometer, depleted, and undrained tests, were performed to survey the impact of adding 1% laponite on the geotechnical properties of free immersed sand. The consequences of one-layered solidification tests demonstrated that the expansion of laponite didn't impact the compressibility of the host sand, yet monotonic undrained tests showed that laponite could diminish rubbing between particles. Moreover, the laponite's capacity to recuperate was assessed by exposing the treated examples to a progression of three cyclic stacking stages. These examples expect up to multiple times more cycles to condense contrasted with untreated sand examples with a comparative relative thickness.

**KEYWORDS:** : Soil nails, Facing of soil nails, Stability of slopes, Inclination of slopes, Vertical inclusions.

### 1.INTRODUCTION

Soil liquefaction is one of the reasons for destroying harm during tremors. Despite the fact that headway has been made in understanding and moderating its belongings, liquefaction actually happens, and conventional strategies to alleviate liquefaction may not be reasonable for huge, populated regions. Thusly, nondisruptive options to miti-entryway liquefaction are required.

Laponite is a manufactured nanocrystalline layered colloid with a substance structure like that of normally happening muds (shape and construction like those of Namontmorillonite, yet one significant degree

more modest in size). In any case, in contrast to regular muds, laponite has no pollutants, making its suspension properties more controllable (BYK Additives and Instruments 2013). At the point when dispersed in water, laponite can change pore liquid into a gel with thixotropic conduct. The standards of this sort of conduct are connected with the level circle state of its precious stones and its substance structure that normally makes its surface have a negative charge and its edges to have a positive charge (Barnes 1997). This characteristic makes the particles combination by electrostatic attaching to frame a total of residue/earth size. At the point when dry laponite particles are added

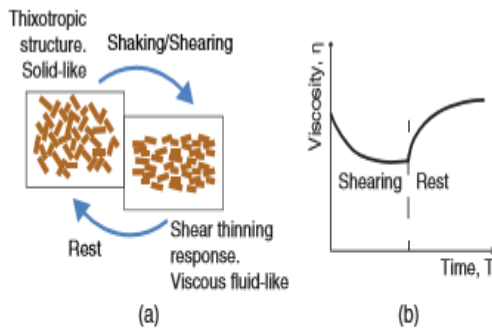
to water, they scatter and improve themselves in a sort of place of-cards development [Fig. 1(a)]. Consequently, at the outset, lapon-ite precious stones structure a Newtonian liquid with a consistency like that of water; in this manner, the suspension could be infused into the ground-water without the requirement for high strain. With time, this development solidifies and turns into a gel with yield shear pressure,  $\tau_{ys}$ , and that intends that assuming the applied shear pressure is lower than this edge the gel acts like a versatile strong. On the other hand, when the shear pressure is higher, i.e.,  $\tau > \tau_{ys}$ , the organization breaks, and the material streams with diminished consistency [Fig. 1(b)] (Barnes 1997). At the point when the shear pressure is eliminated, the gel returns to rest, and the construction starts to recuperate its inside structure, expanding the shear modulus and yield shear strength. On account of this element, it tends to be considered a versatile material.

Its injectability has been concentrated on ineffectively reviewed sand (Mele et al. 2018). It was found that to infuse a suspension at a concentration higher than 3% by weight of water, it is important to utilize an added substance (sodium pyrophosphate).

Concentrates on the rheology of the suspension inferred that 72 h are enough for the suspension to reinforce and foster sufficient shear modulus (El Howayek 2011). In a similar report, cryo-examining electron microscopy (SEM) pictures of examples arranged by two unique strategies, i.e., by dry-blending and by infusion, were looked at; it was presumed that the dry-blending strategy created nonuniform examples, with some air in the middle of between the particles. The

distinction in the grid structure demonstrates that the way of behaving of the dry-blended and penetrated examples wouldn't be something similar. In any case, no examinations distributed to date look at their mechanical ways of behaving.

With respect to's capability to moderate soil liquefaction, Ochoa-Cornejo et al. (2014, 2016) performed cyclic triaxial tests on Ottawa sand examples with 1% laponite powder and tracked down an expansion in the quantity of cycles that arrived at liquefaction, from roughly 100 to 600 additional cycles for a comparable shear anxiety. Huang and Wang (2016) likewise performed cyclic triaxial tests and looked at the expansion, likewise in a dry state, of various measures of laponite (up to 3.5% by weight of sand) and different maturing times (2-6 days); they revealed an expansion in liquefaction obstruction with the expansion of laponite over the long run. Concentrates on in the writing show laponite to be a promising lique-group remediation elective. By and by, research stays restricted with regards to surveying relieving soil liquefaction potential. The accessible information furnish proof that with just 1% laponite (by weight), the quantity of cycles expected for free immersed sand to arrive at liquefaction could be expanded by more than one significant degree. Be that as it may, until this point, laponite has been integrated into soil just in dry circumstances and afterward soaked with water, a cycle unique in relation to genuine field applications. Moreover, the impact of its recuperation expected on the properties of the host sand has not been examined.



**Fig. 1.** Thixotropic behavior of laponite gel: (a) thixotropic behaviour (modified from Barnes 1997); and (b) viscosity curve of a thixotropic material.

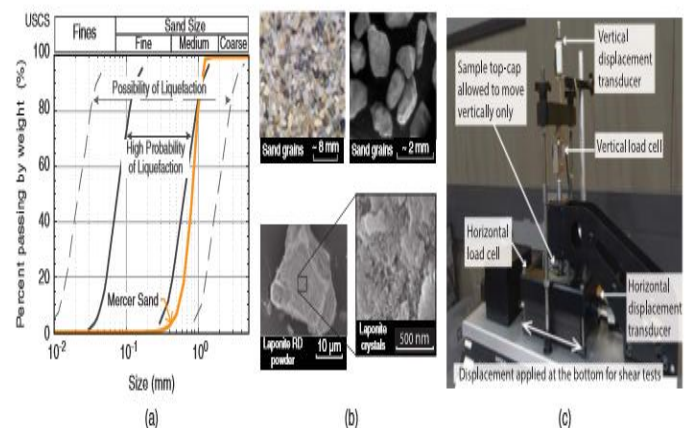
The main objective of the study was to assess the effect of adding laponite in suspension form on the compressibility and shear strength of the host sand. The results provide evidence that this material has the potential as a sustainable alternative to mitigate soil liquefaction and that it could recover its properties after a series of liquefaction events

### Materials

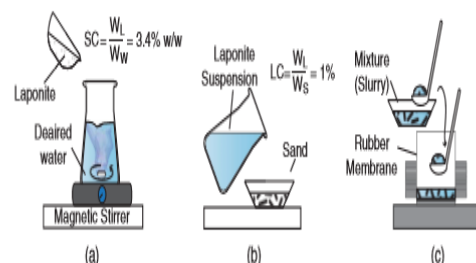
The host sand in this study was a river sand from Waikato, New Zealand (henceforth called Mercer sand, by the name of the village where the quarry is located). Mercer sand has subangular particles, with an average grain size of  $D_{50}$  0.83 mm, and  $D_{10}$   $\frac{1}{4}$  0.31 mm, with poorly graded size distribution ( $C_u$  2.93) and no fines content. The specific gravity is  $G_s$  2.65, and its maximum and minimum void ratios are  $e_{max}$  0.849 and  $e_{min}$  0.631, respectively [ASTM D4253 (ASTM 2014a); ASTM D4254 (ASTM 2014b)]. In this research, the material has been studied in a loose state, with a target relative density of  $D_r$   $\frac{1}{4}$  29% (void ratio of  $e$  0.785) for all tests. Refer to Fig. 2 for its grain size distribution and an image of the particles.

This study involved the use of laponite RD (RD stands for rapid dispersion), a type of laponite that disperses faster in water,

forming a high-viscosity colloidal dispersion (gel-forming grade). When dispersed in water, its nanocrystals [20–30 nm, per Thompson and Butterworth (1992); see Fig. 2 for an image of its particles and crystals] swell and initially form pure and transparent sols that evolve into transparent gel with increasing yield shear point and shear thinning behavior. Its surface area is  $900 \text{ m}^2 \text{ g}^{-1}$  (BYK Additives & Instruments 2014), with a specific gravity of 2.57 (El Howayek 2011; Kroon et al. 1998). Its plasticity index has been reported to be 1,050–1,200 (Al-Mukhtar et al. 2000; El Howayek 2011),



**Fig. 2.** Sand and laponite grain sizes and simple shear device used: (a) grain size distribution curve with established boundaries of liquefaction (Tsuchida 1970); (b) sand and laponite particles; and (c) sample in Geocomp simple shear device.



**Fig. 3.** Sample preparation method with laponite: (a) suspension preparation; (b) slurry preparation; and (c) sample preparation.

which is about twice that of bentonite  
Sample Preparation Method

The specimens were prepared following a modified slurry deposition method (Khalili and Wijewickreme 2008; Kuerbis and Vaid 1988). This method is suitable for



samples with some fines contents (in this case, laponite is considered as fines), with the samples saturated from the beginning. The procedure adopted is depicted in Fig. 3; initially, the laponite suspension was prepared in a concentration of 3.4% by weight of water following the manufacturer's recommendations (BYK Additives & Instruments 2014). To achieve this, deaired deionized water was stirred at 600–1,000 rpm with a magnetic stirrer, and laponite powder was added to the vortex formed in the water and stirred for 20 min until the suspension was clear and without lumps. Then the suspension was thoroughly mixed with sand to form a homogeneous slurry, which was then deposited in the base of the sample holder with a spoon. This method has been reported as one that provides more uniform and replicable specimens (Khalili and Wijewickreme 2008), especially when working with highly gap-graded specimens (laponite crystals are eight orders of magnitude smaller than the average grain of sand). The replicability of the method was assessed through the relative density, which consistently was measured as 29% (2%) for both pure sand and laponite-treated specimens. Note that the void ratio of the sand matrix was kept constant in all samples. All the tests were carried out using the Geocomp ShearTrac II-DSS device (Geocomp Corp., Acton, Massachusetts) [Fig. 2(c)], which meets the setup requirements of ASTM D6528 (ASTM 2007), ASTM D2435 (ASTM 1996), and ASTM D8296 (ASTM 2019), i.e., un-drained conditions are maintained by the constant volume principle and the excess pore water pressure is estimated by the effective stress principle. Previous studies showed that the principle of constant volume could produce practically the

same results as pure undrained conditions (e.g., Dyvik et al. 1987). After sample preparation, all the cylindrical specimens, measuring 63 mm in diameter and 24 mm in height, were placed under water before testing. The samples with 1% laponite were allowed to harden for 72 h under the target consolidation pressure before the start of any testing (consolidation, monotonic simple shear, or cyclic simple shear test)

## Results

### Consolidation Test

Consolidation tests were performed to assess the effect of laponite on the compressibility of the host sand. The tests were performed following NZS 4402 7.1 (NZS 1986). Briefly, the load was applied in several stress increments; at each step, the pressure was kept constant until at least the end of the primary consolidation, computed using the square-root-of-time fitting method (Taylor 1948). Fig. 4 shows the results of the consolidation tests. There were minor differences between the control specimen (pure sand) and the specimen treated with laponite; however, they were within the experimental variability. This means that the sand matrix may control the deformation at the end of each loading step. The coefficient of vertical compressibility,  $m_v = \frac{\Delta \epsilon_v}{\Delta \sigma'_{0v}}$ , is the slope of the curve of the vertical deformation versus the vertical effective stress [Fig. 4(b)]. Within a small stress interval, it is possible to assume that the soil behaves elastically, and soil particles are incompressible. Thus,  $m_v$  is inversely proportional to the confining pressure for most materials. The effect of adding laponite on the compressibility of the specimens appears to be negligible since the differences from the control case are within the bounds of experimental scatter. The coefficient of vertical consolidation,

$C_v$ , represents the rate at which the consolidation process proceeds. A time-dependent parameter, it was computed at each loading stage (not during unloading) using empirical methods: by log-fitting or square-root-of-time-fitting methods (Casagrande and Fadum 1940; Taylor 1948). It directly correlates with the vertical confining pressure, regardless of the type of sample tested, with minimum differences between the two types of specimens [Fig. 4(c)].

### Monotonic Simple Shear Tests

The effect of laponite on monotonic strength was assessed through direct simple shear (SSd) and undrained simple shear (SSu) tests. The SSd tests were conducted at different vertical pressures,  $\sigma_v0$  50–300 kPa, with a displacement rate of 0.1 mm=min, which is considered slow enough to maintain constant effective stress. On the other hand, SSu tests were conducted at different vertical pressures with a range of  $\sigma_v0$  100–300 kPa at a rate of 0.5–mm=min (2%–3.3%=min); this rate made it possible to satisfactorily maintain the specimen's constant volume with minimal change in height, and it is consistent with the testing rates adopted in other studies to produce reliable monotonic stress-strain responses for sands (e.g., Watanabe and Kusakabe 2013; Tatsuoka et al. 2008; Seed and Lundgren 1954).

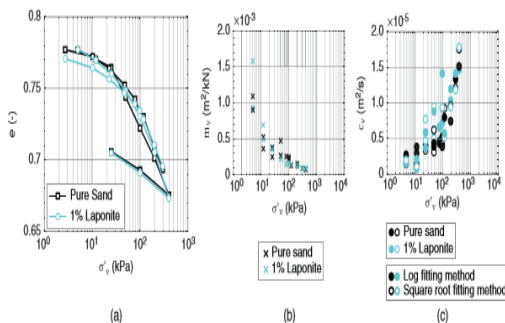


Fig. 4. Results of vertical consolidation on specimens treated with laponite: (a) void ratio versus vertical effective stress; (b) coefficient of compressibility; and (c) coefficient of consolidation.

The results of monotonic tests are presented in Figs. 5 and 6 for SSu and SSd tests, respectively. Under monotonic loading and very large deformation, laponite-treated specimens seemed to perform unsatisfactorily because their shear strength was lower, generally close to half that of the pure-sand samples [Figs. 5(a) and 6(a)]. This is because laponite has a lubricating effect on sand particles, resulting in a reduction of the internal friction angle from  $30^\circ$  to  $20^\circ$ . Because laponite is clay, its addition resulted in an increase in cohesion of the sample from zero to 15 kPa [Figs. 5(b) and 6(b)]. Both types of specimens exhibited a contractive response, but with continuous shearing, the treated samples were less dilative [Figs. 5(c) and 6(c)].

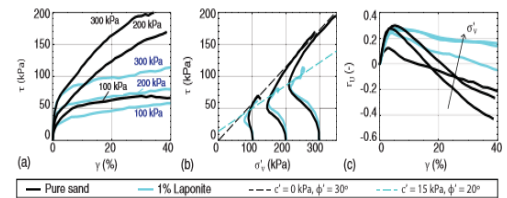


Fig. 5. Effect of laponite on undrained shear behavior of saturated sand: (a) shear stress versus shear strain; (b) stress path; and (c) excess pore water pressure ratio versus shear strain.

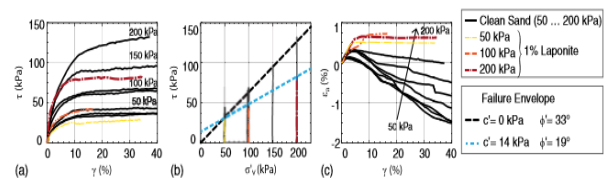


Fig. 6. Effect of laponite on drained shear behavior of saturated sand: (a) shear stress versus shear strain; (b) stress path; and (c) axial strain versus shear strain.

### Cyclic Simple Shear Tests

Undrained cyclic simple shear (CSSu) tests were conducted at a single vertical pressure of  $\sigma_v0$  1/4 100 kPa and different levels of shear stress ratio, CSR 1/4 0.05–0.26, at a frequency of  $f$  1/4 0.5 Hz

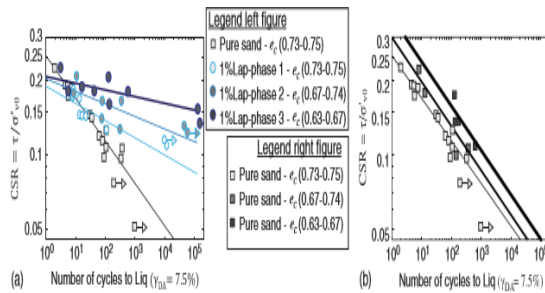


Fig. 7. Cyclic simple shear tests on pure sand and laponite-treated specimens: (a) sand and sand with 1% Lap (3 phases); and (b) sand with diff void ratios.

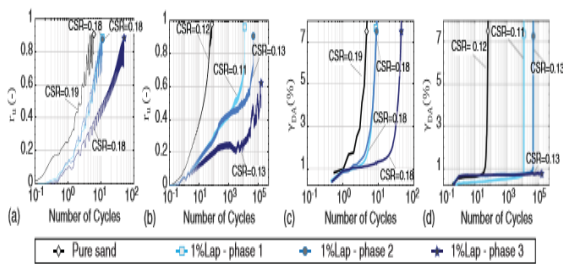


Fig. 8. Comparison of development of excess pore water pressure ratio  $r_u$  and double-amplitude shear strain ( $\gamma_{DA}$ ): (a)  $r_u$  at CSR = 0.18–0.19; (b)  $r_u$  at CSR = 0.11–0.13; (c)  $\gamma_{DA}$  at CSR = 0.18–0.19; and (d)  $\gamma_{DA}$  at CSR = 0.11–0.13.

Additionally, the ability of laponite to recover was assessed by subjecting the specimens to a series of three consecutive cyclic shearing with a resting period of 72 h in between. Furthermore, to consider the effect of densification during the tests, a new set of pure sand samples were prepared with a similar void ratio and tested cyclically. All the specimens' void ratios were computed before the start of each cyclic phase. Hence, these specimens were compared under similar void ratios after consolidation (ec), so that the effect of densification after each cyclic load was considered. Thus, in Fig. 7, the shade of the marker fills is inversely proportional to the value of  $e_c$ . Note that Eq. (1) was used to define the fitting curves, and log-log scale was used in the plots

$$CSR = \frac{1}{4} a \times Nb^{\delta} \Delta P$$

where CSR = cyclic stress ratio; NL = number of cycles required to reach liquefaction (corresponding to 7.5% double-amplitude shear strain); and a and b = fitting parameters

In Fig. 7(a), the control case is compared with laponite-treated specimens subjected to three phases of cyclic loading. Laponite could increase the number of cycles to reach liquefaction up to 100 times. The effect of consecutive phases of cyclic shear application shows that even though the void ratio of the laponite-treated samples decreased after each phase, when compared to pure sand specimens with similar relative density [Fig. 7(b)], these samples not only recovered but also endured even more cycles because the laponite suspension continued to harden with time.

To further highlight the effect of adding laponite, Figs. 8(a and b) show the development of the excess pore water pressure ratio,  $r_u$ , and Figs. 8(c and d) illustrate the cumulative double-amplitude shear strain  $\gamma_{DA}$  at CSR 0.18–0.19 and 0.11–0.13, respectively. Note that in the figures, the excess pore water pressure was estimated from the effective stress principle.

The samples treated with laponite showed a delayed generation of excess pore water pressure and slower shear strain development with the number of cycles, especially at lower CSR [Fig. 8(b)]. For example, at CSR 0.13, the specimen with 1% laponite did not liquefy in Phase 3 and seemed to recover its strength while the test was in progress. Indeed, this specimen underwent more than 105 cycles without developing significant deformation ( $\gamma_{DA} < 1\%$ ). After 103 cycles, the general trend of  $r_u$  started varying more; some instances had  $r_u$  either decreasing or increasing, indicating that the sample was recovering its effective stress while the experiment was still in progress. On the other hand, at higher CSR (0.18–0.19), the pure sand specimen developed  $r_u$  from the start of



shear stress application, while the laponite-treated sample started developing pore water pressure only at the end of the first cycle. The number of cycles required for laponite-treated specimens in Phase 2 is about twice that of Phase 1, whereas Phase 3 requires about four times more cycles for it to liquefy.

### Concluding Remarks

Several laboratory tests were conducted on laponite-treated specimens in order to (1) evaluate the effect of adding laponite on the liquefaction resistance of sand, (2) assess the impact of the self-healing characteristic of laponite on the cyclic resistance of sand, and (3) evaluate the effect of adding laponite on the compressibility and monotonic strength of the host sand. Unlike previous studies where laponite powder was dry-mixed with the soil, laponite was added to the sand in suspension instead.

The effect of laponite on the liquefaction resistance of saturated sand was minor at higher CSRs, but it was considerably larger at lower CSRs, confirming the rate dependence of laponite suspension behavior. Laponite recovery characteristics were assessed by subjecting the specimens to three phases of consolidation and cyclic shear application. The results indicated that with the addition of only 1% laponite by weight of sand, it is possible to significantly increase the liquefaction resistance; if an after-shock occurs, the treatment may be able to resist it. However, given the thinning behavior of laponite suspensions, such effectiveness observed at a lower CSR (0.11) became minor at a higher CSR (0.18).

On the other hand, the results of both undrained and drained monotonic simple shear tests indicated that adding 1% laponite to sand resulted in a

decrease in the friction angle that was not counteracted by an appropriate increase in cohesion; this resulted in an overall strength reduction of the soil under static conditions. Nevertheless, the strength reduction was not as pronounced at a lower confining pressure, e.g.,  $\sigma_v0 = 50$  kPa, where the ground is more likely to liquefy. Thus, if laponite were applied to the shallow portion of soil, it would not affect the static strength very much, but it could delay the occurrence of soil liquefaction. Therefore, this should be the target depth for treatment. Finally, the addition of laponite has a negligible effect on the consolidation behavior of the host sand.

Based on these findings, laponite could serve as an alternative solution to mitigate liquefaction, especially in populated areas where conventional mitigation methods are difficult to implement. With its low initial viscosity, laponite can be injected or delivered into the ground as in passive site remediation. Hence, not only would adding laponite in suspension (say, by a slurry deposition method, as used in this study) modify the pore water completely, but the rheology of the laponite would be more representative of how it behaves in real field applications.

In the future, the stability and durability of the treatment should

be assessed, particularly the effects of drying-wetting cycles, additional cation or anion exchange, and laponite crystallization of the treatment, among others. More tests are planned to address these issues.

### Data Availability Statement

Some or all data that support the findings of this study are available from the corresponding author upon reasonable request.

## Acknowledgments

The authors would like to acknowledge the IMCD New Zealand Limited for providing the laponite RD used for this study.

## Notation

The following symbols are used in this paper:

a, b = fitting parameters in liquefaction curves;

Cu = coefficient of uniformity;

Cv = coefficient of vertical consolidation;

c0 = effective cohesion;

Dr = relative density;

D10 = effective particle diameter (size at 10% finer by weight);

D50 = mean particle diameter;

e = void ratio;

ec = void ratio after consolidation;

emax = maximum void ratio;

emin = minimum void ratio;

f = frequency;

Gs = specific gravity of particles;

k = coefficient of permeability; mv = coefficient of compressibility; N = number of cycles;

NL = number of cycles required to reach liquefaction;

ru = excess pore water pressure ratio;

T = time;

WL = weight of laponite;

WS = weight of sand;

$\alpha$ ,  $\beta$  = fitting parameters in pore pressure generation curves;

$\gamma$  = shear strain;

$\gamma_{DA}$  = double-amplitude shear strain;

$\epsilon_a$  = axial strain;

$\epsilon_v$  = volumetric strain;

$\eta$  = viscosity;

$\sigma_v$  = effective vertical stress;

$\sigma_v^0$  = initial effective vertical stress;

$\tau$  = shear stress;

$\tau_{ys}$  = yield shear stress; and

$\phi^0$  = effective internal friction angle

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