Dynamic Behavior of Sand with NanoParticles

Comportement dynamique de Sable avec Nanoparticules

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ABSTRACT: This work presents an experimental investigation to examine the effect of Laponite -a synthetic nanoclay with high plasticity- on the dynamic behavior of sands. The experimental program considers cyclic triaxial and resonant column tests on specimens of pluviated sand and Laponite. Microstructure observation address the granular fabric and the sand-Laponite interactions. Cyclic triaxial tests show that 1% of Laponite impacts the cyclic behavior, improving the liquefaction resistance over one order of magnitude compared to clean sands. Resonant column tests show that the small strain stiffness of the sand (G_0) increases with 1% of Laponite. The overall results show that Laponite extends the linear threshold of deformation, reduces stiffness degradation, and delays excess pore pressures. Microstructure observations suggest that Laponite reduces sand particle mobility by the formation of a pore fluid with solid-like properties.

RÉSUMÉ: Ce travail présente une étude expérimentale pour examiner l'effet de la Laponite -une nanoargille synthétique avec une plasticité élevée- sur le comportement dynamique des sables. Le programme expérimental envisage des essais triaxiaux cycliques et de colonne résonnante sur des échantillons de sable pluvié et de Laponite. L'observation de la microstructure concerne le tissu granulaire et les interactions sable-Laponite. Les essais triaxiaux cycliques montrent que 1% de Laponite affecte le comportement cyclique, améliorant la résistance à la liquéfaction sur un ordre de grandeur par rapport aux sables propres. Les essais de colonnes résonantes montrent que la rigidité à faible déformation du sable (G_0) augmente de plus de 20% avec 1% de Laponite. Les résultats globaux montrent que la Laponite prolonge le seuil linéaire de déformation, réduit la dégradation de la rigidité et retarde les pressions de pores en excès. Les observations de microstructures suggèrent que la Laponite réduit la mobilité des particules de sable par la formation d'un fluide poreux à propriétés solides.

KEYWORDS: Nanoparticles, Liquefaction, Cyclic Triaxial Tests, Resonant Column Tests, Microstructure.

1 INTRODUCTION

Liquefaction is a large-strain phenomenon occurring in saturated loose sand deposits during earthquakes causing large ground deformations, and significant damage to civil and industrial infrastructure (Ochoa-Cornejo et al. 2016; Youd et al. 2001). Liquefaction occurs as cyclic shear induces particle mobility; as undrained conditions prevail during earthquakes, excess pore water pressures generate, decreasing the effective stresses with each cycle of loading. Eventually, a transient condition of zero effective stress is reached, initiating liquefaction, large deformations, and ground failure (Castro 1975; Ishihara 1993). Liquefaction and its catastrophic damage were first observed in 1964, in the Alaska and Niigata Earthquakes, both of magnitude higher than Mw9.0 (Youd 1978), causing settlement and collapse of urban/industrial structures on saturated loose sand deposits. Liquefaction has also been observed in earthquakes such as El Maule 2010, Christchurch 2010, and Tohoku 2011 (Bhattacharya et al. 2011, Bradley 2012, Verdugo 2012).

Liquefaction research initially focused on clean sands, and the factors controlling the behavior and resistance of sands against this phenomenon (Castro and Poulos 1977; Seed and Lee 1966; Seed et al. 1975). These studies highlighted the effect of the soil type, void ratio, initial effective confinement, overconsolidation ratio, and static shear on liquefaction. These studies concluded that liquefaction occurs mainly in sands; that for soils of similar nature, the higher the void ratio, the higher the liquefaction potential. Also, the higher the overconsolidation ratio, the higher the liquefaction resistance; and that it can manifest as either cyclic mobility or flow failure, depending on the initial static shear induced in the mass of soil.

In the field, sand deposits are not clean. They have various percentages of fines of low-to-medium plasticity and even cementation. Studies on the effect of fine soils and cementation on liquefaction were popular in the 80's and 90's (Ishihara and Koseki 1989; Poulos et al. 1985; Troncoso and Verdugo 1985, Vaid and Sivathayalan 1996). Some authors suggested that the presence of fines reduces the liquefaction resistance (Troncoso and Verdugo 1985), while others suggested that liquefaction increases depending on the percentage of fines and plasticity (Koester 1994). Other studies found that plastic fines with PI > 10, as well as cementation, increase the liquefaction resistance (Clough et al. 1989; Ishihara and Koseki 1989).

Since the early 2000's, research efforts have aimed at developing methods to strengthen liquefaction resistance. The methods can be either active or passive. Active methods induce the densification of the soil with high energy sources, rearranging sand particles into a denser structure (vibro-compaction, dynamic compaction, and blast densification). Passive methods impact the soil behavior without affecting the fabric of the soil skeleton. They are more suitable in areas where civil infrastructure is close to, and around, the site of construction. For instance, a popular passive technique is the permeation grouting, which drills a bore, followed by the injection of a probe and the permeation of grouting material, without altering the fabric. However, this method can be time-consuming and expensive.

The positive outcomes of liquefaction research during the last decades encouraged the development of new passive methods to improve the soil right beneath constructed sites without disturbance. Examples of these techniques are the biocementation, colloidal silica grout, or the pore fluid engineering methods (El-Mohtar et al. 2013; Gallagher and Mitchell 2002; De Jong et al. 2006; Ochoa-Cornejo et al. 2016).

Particularly, the pore fluid engineering method engineered a viscous thixotropic fluid in the void space of the sand skeleton with Bentonite solutions, increasing the liquefaction resistance. This increase was due to the extended elastic behavior of the granular soil induced by the high thixotropy of bentonite suspensions; in water, Bentonite forms a thixotropic fluid with a viscosity that increases with concentration and aging. The viscosity of bentonite suspensions is controlled to permeate it into the pore space between sand particles. As a result, the sand can withstand higher levels of shear strain. These findings were within the framework of an experimental program that considered the performance of cyclic triaxial and resonant column tests (El Mohtar et al. 2013).

Bentonite is natural and safe, but complicated to implement in the field; Bentonite suspensions require chemical treatment to permeate it. The treatment aims at controlling the short-term viscosity and the rheological properties of the suspensions with sodium pyrophosphate (SPP). In addition, Bentonite suspensions might not be injectable in sands with fines.

The experience with Bentonite encouraged to move forward by using Laponite, a synthetic nanoparticle. The use of Laponite skips/overcomes chemical treatment, particle gradation, and impurities. The clay-type particle Laponite is manufactured with a diameter ten times smaller than Bentonite, and it has a naturally delayed gelation period, allowing the permeation of larger soil volumes, respect to Bentonite. Also, Laponite has a higher plasticity index than Bentonite (1100 over 650), which would require smaller quantities of Laponite to strengthen the soil against liquefaction.

2 MATERIALS, EQUIPMENT, AND EXPERIMENTS

2.1. *Materials*

This research used Ottawa Sand (C778) and Laponite RD. Ottawa sand is a clean uniform silica sand of fine-to-medium size. Its specific gravity, G_s, is 2.65, with e_{max}=0.480, and e_{min}=0.783 (Ochoa-Cornejo, 2015). Laponite RD is a synthetic nanoclay manufactured and commercialized by BYK Additives and Instruments. It is used as a rheology modifier in industries such as the cosmetics, inks, paints, and surface coatings. Single Laponite particles have a disk-like shape of ~25 nm in diameter and ~1 nm thickness. It is a 2:1 clay formed by a magnesium octahedral sheet sandwiched between two tetrahedral silica sheets (Figure 1(a)). Laponite has negative charges on both faces, and positive charges on the rim (Figure 1(b)). Its specific gravity is 2.57, and a plasticity index (PI) of ~1100% (El Howayek 2011), significantly greater than Bentonite (PI of ~350). In water, Laponite hydrates and swells, forming a monodisperse suspension. Laponite dispersions have early Newtonian behavior and delayed gelation process (Mongondry et al. 2005; Mourchid et al. 1995)).

2.2. *Specimen Preparation and Testing Procedures*

Cyclic Triaxial and Resonant Column tests were conducted on dry pluviated specimens of clean sand, and sand with Laponite prepared at 1% of the nanomaterial by-dry-mass of sand. The skeleton relative densities of the specimens, Dr_{sk}, ranged between 15% and 25%, considering the e_{max} and e_{min} of the clean sand. The specimens were flushed with carbon dioxide (CO_2) and de-ionized de-aired water, 200-300 kPa of backpressure, and B-values of 0.95. Specimens were isotropically consolidated to effective stresses of 100 kPa. Clean sand specimens were sheared after one hour of aging, while sand-Laponite specimens were aged for 72 hours. This period was found to be the time at which the developed rheological properties of Laponite pore fluid in the pore space reduced liquefaction susceptibility. In the case of triaxial testing, undrained cyclic loading was conducted with a vertical loading frequency of 1 Hz, and cyclic stress ratios that ranged between 0.1 and 0.25. For Resonant Colum tests, undrained cyclic loading was applied at resonance conditions. Resonant frequencies ranged between 50 Hz and 150 Hz. The angular amplitudes induced shear strains between 10^{-4}% and 10^{-2}%, allowing the measure of the shear modulus as a function of shear strain in both linear and non-linear regime of deformation.

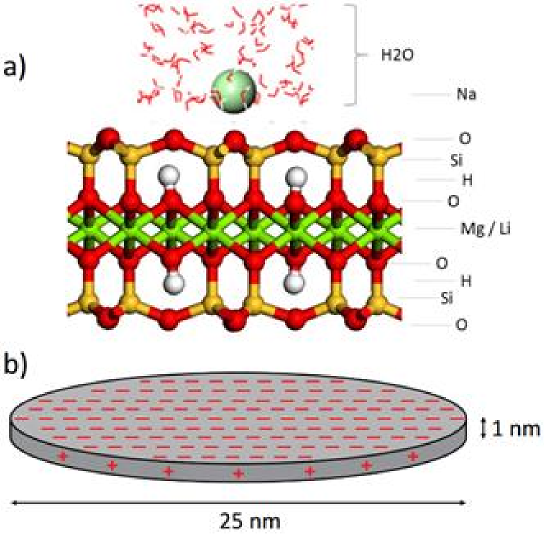

Figure 1. a) Structure of Laponite, and b) geometry of individual Laponite particles.

3 EXPERIMENTAL RESULTS

3.1. *Undrained Cyclic Triaxial Tests Results*

Figure 2 presents the results from cyclic triaxial tests performed on specimens of clean sand, and sand with 1% of Laponite specimens. The horizontal axis, in logarithmic scale, is the number of cycles to liquefaction. The vertical axis is the cyclic stress ratio at which the tests were conducted. The arrow in this figure indicates the number of cycles where the indicated test was terminated after the specimen reached a state of constant excess pore pressure, exhibiting no liquefaction. Figure 2 shows that, for all the specimens, the number of cycles to liquefaction (N_{Liq}) decreases as the level of applied cyclic shear (CSR) increases. In addition, at the same CSR, the liquefaction of the sand-Laponite specimens occurs at a number of cycles that is over one order of magnitude with respect to clean sand specimens. There is a significant increase in the cyclic resistance due to the addition of 1% Laponite in the matrix of sand. In this study, the liquefaction criteria used was 100% of excess pore pressure relative to the initial effective stress, σ'_0, also known as 'Initial Liquefaction' (Castro 1969).

3.2. *Undrained Resonant Column Tests Results*

This section presents the results from the Resonant Column tests performed in both clean sand and sand with 1% of Laponite.

There is a significant reduction of the shear modulus for shear strain levels beyond ~10^{-3}%. Therefore, this strain value appears as a transition point from linear to non-linear deformation regime. (e.g. Drnevich 1985; Khan and Cascante 2008). In this context, the resonant column tests would allow appreciating the effects of Laponite at small strain levels. During the undrained shearing phase of resonant column testing, shear strains ranged between 10^{-4} %, a state of "intact" soil fabric, and ~10^{-2} %, where deformations become significant (Cascante and Santamarina 1996). Figure 3 shows the results of tests conducted on specimens of clean sand, and sand with 1% of Laponite, at initial effective stresses of 100 kPa. This figure shows how the shear modulus decreases with the cyclic shear strain, in logarithmic scale. It is interesting to note that the shear modulus of specimens of sand with 1% Laponite is higher than the shear modulus of clean sand specimens over the entire range of cyclic shear strains.

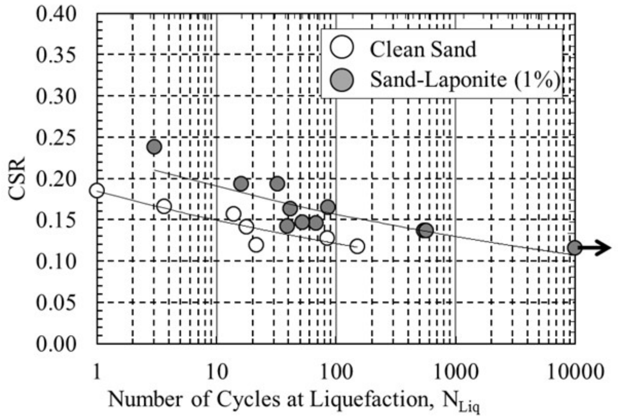

Figure 2. The cyclic resistance of clean sand, and sand with 1% of Laponite. Skeleton relative densities between 15% and 25%.

Figure 4 shows the data in Figure 3 with the normalization of the values of the shear modulus by G_0, which is the shear modulus measured at the start of the shearing stage, at very small strains. This normalization highlights the degradation response of the studied specimens. They present –practically- a constant value of the shear modulus up to shear strains of ~10^{-3}%. Beyond this threshold, the curves show a similar reduction in the shear modulus up to a shear strain of $4x10^{-3}$ %, when G/G_0=0.9. For shear strains higher than $4x10^{-3}$%, the curves start to diverge, with the clean sand exhibiting the most significant degradation.

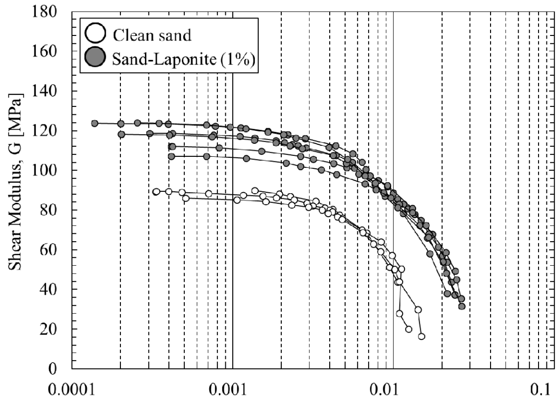

Figure 3. Variation of the shear modulus of clean sand, and sand with Laponite, as a function of shear strain (σ'_0=100 kPa).

3.3. *Granular Microstructure Imaging*

Figures 2, 3, and 4 show that the presence of Laponite inside the sand matrix induces a positive effect on its cyclic behavior and resistance. The results also suggest that the plasticity of the fines plays an important role in the cyclic response of the soil; only 1% of Laponite induces a significant improvement in liquefaction resistance.

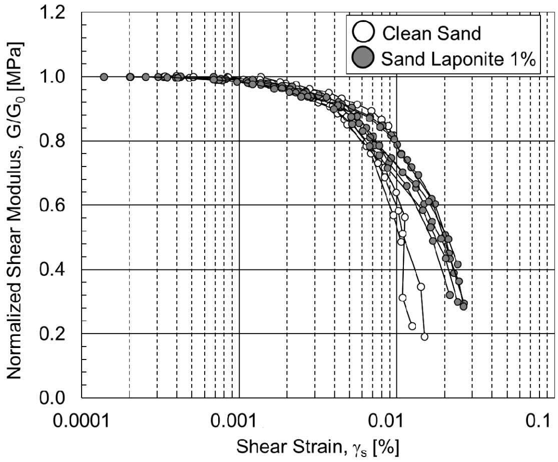

Figure 4. Variation of the normalized shear modulus in specimens of clean sand and sand with Laponite.

The improvement of liquefaction resistance with the addition of Laponite is caused by a delay in the decrease of the effective stress during cyclic loading. The delay is attributed to the interaction between the thixotropic fluid formed by Laponite and water in the pore space of the granular material. The pore thixotropic fluid reduces sand particle mobility, delaying the decrease of effective stresses, and therefore increasing the number of cycles to trigger the liquefaction of the sand. Figure 5 presents a cryo-SEM image of sand with 1% of Laponite. It is observed that sand grains are surrounded by a cellular matrix of gel in the pore space between sand grains. This structure would stiffen the structure, increasing the elastic response of the sand/clay mixture. Therefore, plastic deformations are reduced inducing the delay of excess pore pressure generation, and therefore the decrease of effective stresses.

4 CONCLUSIONS

This paper presented an experimental research performed to examine the behavior of sand 1% of Laponite RD, a synthetic clay of high plasticity. The experiments included cyclic triaxial and resonant column tests on clean sand specimens and sand-Laponite specimens prepared at skeleton relative densities of 20% ±5%. The tests on clean sand provided the benchmark to quantify the effects of Laponite. Cyclic triaxial tests were conducted at effective stresses of 100 kPa, with cyclic stress ratios (CSR) of up to 0.25, using as liquefaction criterion 100% of excess pore pressures. The resonant column tests were performed at similar testing preparation conditions but sheared in the small to medium regime of deformation, i.e., between 10^{-4}% to 10^{-2}%. The mechanical tests were complemented with Scanning Electron Microscopy (SEM) observations of sand-Laponite structure in wet conditions.

Cyclic triaxial test results indicate that 1% of Laponite renders a significant increase in the liquefaction resistance of sands. The results provide supporting information to those presented by El Mohtar (2008) using bentonite. Given the high plasticity of Laponite, smaller dosages of laponite may be required to achieve an increase in liquefaction resistance, compared to the improvement observed with bentonite.

Resonant column test results show an extension of the linear threshold during cyclic loading relative to clean sand. This observation is important evidence regarding the reduced mobility of sand particles due to the effect of Laponite. The observed results suggest the formation of a pore fluid with solid-like properties in the pore space, as a result of the hydration of Laponite in between sand grain particles.

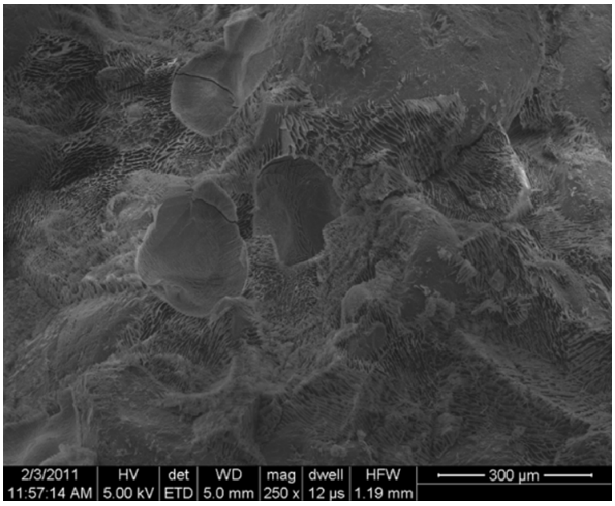

Figure 5. SEM photographs of dry mixed specimens of sand with 1% Laponite.

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