Discussion on: “Laboratory investigation of liquefaction mitigation in silty sand using nanoparticles” [Eng.Geol.204:23-32]

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Introduction

This discussion addresses the results presented in the paper entitled “Laboratory investigation of liquefaction mitigation in silty sand using nanoparticles” by Professors Huang and Wang (2016) (herein referred to as “the authors”) from Tongji University. This topic is of great interest to the writers of this discussion (herein referred to as “the discussers”), who have been investigating the use of laponite as a liquefaction mitigation agent for several years, and have published the first evidence on the effect of laponite in increasing the liquefaction resistance of sands (Ochoa-Cornejo et al. 2014). The results by Huang and Wang (2016) provide indeed additional support to the potential of this method for liquefaction mitigation.

The approach followed by the authors in the paper is generally similar to that employed by the discussers in their research, funded by the US National Science Foundation (Grant #0928679, 2009), and documented in El Howayek 2011; El Howayek et al. 2014, Santagata et al. 2014; Ochoa-Cornejo et al. 2014, 2016; Ochoa-Cornejo 2015. Both studies included extensive cyclic triaxial testing of sand-laponite specimens prepared by dry mixing to measure the effects of the presence of laponite on the resistance to liquefaction; characterization of the rheology of the laponite dispersions through viscosity measurements and amplitude sweeps to gain insight into the response of the pore fluid formed in the presence of laponite in the pore space; and direct observations of the microstructure of laponite dispersions and sand-laponite mixtures using cryo-SEM.

The similarities between the approaches provide the opportunity to compare the outcomes of the two studies, thus contributing to the increased understanding of the mechanisms by which laponite alters the behavior of sands under cyclic loading, and stimulating continued research in this area. With these objectives in mind, the discussion (1) compares select results obtained by the discussers on the cyclic

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resistance of sand with laponite to those presented by the authors in the paper, showing that the two studies overall provide a consistent picture of the effects of small percentages of laponite on the liquefaction resistance; 2) highlights how, based on experimental results, differences in response may be expected when the treatment is implemented through permeation, rather than by dry mixing sand and laponite; 3) presents previously unpublished data obtained testing laboratory specimens permeated with concentrated laponite dispersions, that encourage continued research on the use of laponite.

Cyclic resistance of sand-laponite mixtures: comparison of data from two studies

The primary emphasis of the paper by Huang and Wang is to demonstrate the increased resistance to liquefaction of sand specimens in the presence of small percentages of laponite. This is achieved through tests conducted on specimens prepared with laponite concentrations of 0, 2%, 2.5%, 3%, and 3.5% (expressed, according to the paper, as “the ratio of dry laponite particles to added deionized de-aired water”). Improvements in cyclic resistance, measured by the number of cycles to liquefaction sustained by specimens under a given cyclic stress ratio are reported in the presence of laponite. Increasing dosages of laponite and extended duration of what the authors refer to as the “curing” time are found to further contribute to improve the response.

Overall, these results are consistent with the discussers’ cyclic triaxial data documented in detail in Ochoa-Cornejo et al. (2014 & 2016) and Ochoa-Cornejo (2015), which were also obtained testing specimens of sand mixed with laponite prior to specimen formation. Comparison of the two data sets requires consideration of the methodologies used, in particular with regard to:

- *the materials tested*, clean Ottawa sand (with $e_{\min}=0.48$, $e_{\max}=0.78$, $C_u=1.48$, less than 1% passing the #200 sieve) was used in the work performed by the discussers versus a sand from Changxing Island in Shanghai ($C_u=2.15$, ~23% passing the #200 sieve [values estimated from Figure 1 in the paper]) in the paper by Huang and Wang (2016). Laponite RD manufactured and commercialized by BYK Additives and Instruments (previously Rockwood Additives Inc.) was employed by the discussers. No information on the grade of laponite used is provided by Huang and Wang (2016).
- *the specimen preparation procedure*: in both studies sand and laponite were dry mixed prior to specimen formation. The procedures followed, differ, however in two respects: in the time at which water was added to the mixture, and in the method used to form the specimens. Specifically, in the work by Huang and Wang (2016) water was added prior to *compaction* of the mixture in a rigid mold, while in the study performed by the discussers, water was flushed through the specimen prepared by *dry pluviation* following setup in the triaxial cell.
- *the density of the cyclic triaxial specimens*: in the work by the discussers testing focused on specimens with the same skeleton relative density of 15-25%, corresponding to values of the skeleton void ratio in the 0.705-0.735 range. Unfortunately, the paper by Huang and Wang does not report relative density values nor $e_{\min}$ and $e_{\max}$ for the sand investigated.

- the *laponite dosages*: values of the laponite dosages (2% to 3.5%) are reported in the paper by Huang and Wang in terms of “the ratio of dry laponite particles to added deionized de-aired water.” While these values do not account for the additional water required for saturation of the specimens following setup, they are likely close to the concentration of the laponite in the pore fluid. When expressed as concentration of the laponite in the pore fluid, the data from the discussers’ work presented in Figure 1 below falls at the high end of this range (~ 3.6%) (note that in the discussers’ original papers cited, this laponite dosage is expressed as 1% by dry mass of the sand).
- the *testing procedures*: the two studies differ in the pre-shear effective stress level (30 kPa versus 100 kPa) and the frequency of the applied cyclic load (0.1 Hz versus 1 Hz). Another, perhaps more impactful, difference is in the 2-6 day “curing” period allowed prior to specimen setup in the work by Huang and Wang, and the three day post-consolidation aging stage adopted in the work by the discussers.

Having acknowledged some differences between the two studies, Figure 1(a) presents plots of the number of cycles to liquefaction determined based on the initial liquefaction criterion (i.e. in correspondence to the excess pore pressure reaching a value equal to the initial effective confinement) versus the applied cyclic stress ratio that includes data from the two studies. In this figure the data obtained by the discussers for sand with laponite (circular gray symbols) falls at the low end of the range formed by the results provided by Huang and Wang (solid black symbols – only data for 2 day curing period are presented). Note, however, the different position of the curves for the clean sands from the two studies, with the data for Ottawa sand (empty circles) falling considerably below those for the silty sand (empty diamonds) studied by Huang and Wang. The position of these data, which represent the baseline against which the effects of the addition of laponite are evaluated, reflect differences in sand characteristics and relative density. To, at least in part account for such differences, Figure 1(b) shows a plot of the cyclic stress ratio corresponding to a given number of cycles to liquefaction, normalized by the CSR applicable to the clean sand. This is the same approach for quantifying the improvement in the cyclic resistance associated with the presence of laponite adopted in the authors’ paper. The data from Huang and Wang reported in Figure 1(b) were derived from Table 2 in the paper, which show the CSR corresponding to 5, 12 and 30 cycles to liquefaction. In this figure the discussers’ data derived from the best fit curves shown in Figure 1(a) are again plotted with circular gray symbols.

The results of both studies demonstrate an improvement in cyclic resistance in the presence of very small percentages of laponite. For laponite dosages of 3-3.6% (all reported here expressed as concentration of the laponite in the pore fluid), the improvement as measured by the increase in CSR that can be sustained for a given number of loading cycles, exceeds 50% in the two studies. Based on both the results presented in the paper, and additional data obtained by the discussers (Ochoa et al. 2016), even greater improvements are observed with time. Note that while the data provided by the discussers display an essentially constant $CSR_{\text{sand w/lap}} / CSR_{\text{clean sand}}$ up to 200 cycles (Fig. 1(b)), this same ratio

shows a marked decrease with number of cycles in the results by Huang and Wang. This decrease is noted by the authors in the paper. The deviation between the two data sets may be a reflection of differences in fabric associated with the different specimen preparation procedures. Specimen preparation procedures are known to be a factor even in clean sands, and should be expected to play an even more marked role in the case of mixtures of sand and laponite. In particular, given the strong attraction under dry conditions of the silt size laponite aggregates to the surface of the sand grains (see Ochoa-Cornejo 2015), and the affinity of laponite to water, the time at which the clay is exposed to water and the “curing” and aging durations should have a significant impact on the specimen fabric, and thus on the physical mechanisms governing particle-particle and particle-pore fluid interactions during cyclic loading. Finally, it should be noted that beyond the increase in the number of cycles to liquefaction, Ochoa-Cornejo et al. (2016) show that the presence of laponite impacts all stages of pore pressure generation during cyclic loading.

Microstructure and mechanisms for cyclic resistance: dry-mixed versus laponite permeated specimens

Moving on to the second objective of this discussion, it must be noted that in field applications, as recognized by the authors in the paper, treatment with laponite would be implemented through permeation of a porous medium by the laponite in dispersion form. The authors state that the “permeation method is very sensitive and difficult to control,” and this appears to be their primary motivation for limiting testing to dry mixed specimens. This is undoubtedly the case at the field scale, primarily due to variability in soil conditions. While solutions to deliver the laponite in dispersion form in the field will need to be developed to eventually ensure the practical feasibility of this approach to liquefaction mitigation, there is another question that must be addressed, and that is whether the results of tests on dry mixed specimens can be extrapolated to permeated conditions.

The discussers have successfully been able to permeate laboratory sand specimens with concentrated laponite dispersions, and have collected limited data following permeation, allowing comparisons to be made between the response of dry mixed and permeated specimens. Results from hydraulic conductivity measurements in a modified oedometer using the falling head method and shear stiffness degradation curves derived from resonant column tests are discussed below to: a) highlight differences in fabric between these two specimen types; and b) to provide some insight into the response of permeated specimens.

Falling head tests were performed by El Howayek (2011) on specimens permeated with 3% laponite dispersions (by mass of the water) and dry-mixed specimens prepared with the same amount of laponite (i.e. an amount that when fully hydrated generates the same concentration in the pore fluid as that of the laponite dispersion) alongside the reference value for the clean sand. The data, which were all obtained 4 days after the laponite gained access to water, indicate that the hydraulic conductivity of the permeated specimens is one order of magnitude lower relative to that of the dry mixed specimens

prepared with the same amount of laponite. These values of hydraulic conductivity fall ~ 2 and 3 orders of magnitude below that measured on clean sand specimens ($\sim 8 \times 10^{-3}$ cm/s) prepared at the same relative density. The discrepancy in the values of hydraulic conductivity is thus a reflection of differences in the fabric formed in the two types of specimens as a result of the different preparation procedures: in the permeated specimens, laponite is premixed with water at a high shear rate, which promotes complete hydration of the laponite particles and results in a uniform pore fluid. Moreover, provided that the injection gradient is maintained low, permeation should not cause separation of the grains and/or presence of the laponite at the grain contacts. In contrast, in the dry mixed specimens, the laponite already present in the sand matrix, including at the sand grain contacts, gains slow access to water, and may not completely hydrate. Additionally, even once hydrated, at least for the laponite dosages considered here, given the higher hydraulic conductivity measured in the dry mixed specimens, the laponite does not appear to be able to fully occupy the pore space. This hypothesis is supported by cryo-SEM images of samples extracted from the specimens used for the falling head tests on dry mixed and permeated specimens presented by El Howayek et al. (2014): the images for the dry-mixed specimens show the presence of pockets with no laponite, which El Howayek et al. (2014) hypothesize “represent regions occupied by water or by lower concentration laponite suspensions formed after flushing the dry mixed specimens.” The same micrographs also indicate a denser laponite gel network in proximity to the sand surfaces and inter particle contacts, likely a result of the adhesion of the dry laponite powder during the specimen preparation procedure. Neither of these features is observed in the permeated specimens.

Overall, these observations highlight some fundamental differences between the fabric of dry mixed and permeated specimens, which should be expected to have an impact on the mechanisms that control the response to cyclic shear, and thus the resistance to liquefaction. In their paper, Huang and Wang refer to two mechanisms as responsible for the greater resistance to liquefaction measured in the dry mixed sand laponite specimens: a) the formation of a solid gel between the grains and b) “soil grain cementation” by the laponite gel. They indicate that cryo-SEM images provide evidence of the second mechanism.

The discussers first suggested the role of a solid-like pore fluid in limiting particle mobility during cyclic loading (El Mohtar et al. 2013, Santagata et al. 2014). Based on recent work with laponite (Ochoa-Cornejo 2015; Ochoa-Cornejo et al. 2016), they proposed that at least the following two mechanisms, akin to those cited by the authors, come into play in the case of dry mixed sand laponite mixtures: (1) bonding/bridging due to the presence of the laponite at and around the sand grain contacts, and (2) formation of a pore fluid with solid like properties, as a result of the hydration of the laponite present in the porespace. Both contribute to limiting particle mobility during cyclic loading. However, Ochoa et al. (2016) suggest that for “low” dosages of laponite (such as the ones reported in Figure 1), the first mechanism plays a primary role in increasing the resistance to liquefaction. This hypothesis is supported by observations from a range of tests, including resonant column data showing an increase in the shear stiffness at very small strain relative to clean sand (see Ochoa-Cornejo et al. (2016) and Ochoa-Cornejo (2015) for details and for a discussion of the effects of increasing the dosage of laponite). From an

application perspective this is potentially an important issue, as this mechanism may not be enabled when laponite is delivered in the pore space in dispersion form, as would occur in the field.

Behavior of laponite permeated sand from resonant column tests

Having cautioned against the direct extrapolation of results from dry mixed specimens to permeated conditions, the discussers would like to end this discussion of the paper by Huang and Wang, presenting resonant column data from permeated specimens that support the hypothesis that the presence of the laponite gel in the sand pore space can limit particle mobility during cyclic loading. Figure 2 shows data obtained from nine tests: five conducted on specimens of clean Ottawa sand ($D_r=24.5\%\pm1.2\%$), the other on specimens of similar relative density ($D_r=25.5\%\pm4.4\%$), permeated first with water and then with 3%-3.5% laponite dispersions. All specimens were isotropically consolidated to 100 kPa, and tested undrained, following a 3 day aging stage. This period is sufficient for the laponite dispersion used to permeate the specimens, which immediately after mixing has Newtonian behavior with viscosity 5-7 times that of water, to develop its gel structure and the desired solid-like response. In the figure the curves for the laponite-permeated specimen lie to the right of the band formed by the clean sand data, indicating an extension in the linear threshold and less significant reduction in shear stiffness at any strain level (e.g. for $G/G_{\max}=0.80$, $\gamma=0.010\%\pm0.001\%$ for laponite permeated specimens versus $0.007\%\pm0.001\%$ for clean sand), overall reflecting a reduced mobility of the sand grains. Consistent with the reduced non-linearity, the laponite permeated specimens also exhibit a retarded generation of excess pore pressure compared to clean sand. It is important to note, however, that while delayed excess pore pressures are expected and such behavior is consistent with the observed reduction in shear stiffness degradation, the actual values of the excess pore pressures recorded may be smaller than those present in the specimen. This is due to sensor response issues when measuring pore pressures in sand specimens saturated with a gel. Overall, these results suggest that when delivered in the soil in dispersion form, laponite may be able to limit particle mobility and thus delay excess pore pressure generation during cyclic loading.

Outlook for the future

The data collected by both the authors and the discussers provide preliminary evidence of the potential for laponite to function as a liquefaction mitigation agent, and encourage continued research in this field. Additional work is required before the methodology can be considered ready for field trial. To close this gap, it is recommended that future efforts should be directed at:

- validating the method in the laboratory under field relevant conditions, shifting the focus to cyclic triaxial testing of laponite permeated specimens;
- addressing issues related to laponite delivery in a porous medium, taking into account the spatial variability that is characteristic of field conditions;
- assessing the effectiveness of the treatment beyond element tests.

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Figure 1. a) Relationship between cyclic stress ratio (CSR) and number of cycles to liquefaction for clean sands and sands dry mixed with laponite; b) effect of laponite on the CSR corresponding to a given number of cycles to liquefaction (all laponite percentages expressed as concentration of the laponite in the pore fluid, i.e. with respect to water).

Figure 2. Normalized shear modulus and normalized excess pore pressure generation, as a function of the shear strain for laponite permeated and clean sand specimens.