

Cyclic behavior and pore pressure generation in sands with laponite, a super-plastic nanoparticle



Felipe Ochoa-Cornejo^a, Antonio Bobet^b, Cliff T. Johnston^c, Marika Santagata^{b,*}, Joseph V. Sinfield^b

^a Civil Engineering Department, University of Chile, Beauchef 850, Santiago of Chile, Chile

^b School of Civil Engineering, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907, United States

^c Department of Agronomy, Purdue University, 915 W State Street, West Lafayette, IN 47907, United States

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ABSTRACT

The paper examines the effect of the presence of small percentages (1–5%) by dry mass of the sand of laponite – a synthetic nanoclay with plasticity index exceeding 1000% – on the cyclic response of sand with relative density in the 15–25% range. The work is based on cyclic triaxial tests performed on specimens prepared pluviating sand and laponite under dry conditions and then permeated with water. 1% laponite impacts all stages of the cyclic tests, from the response during the first loading cycle to liquefaction, increasing the cyclic resistance. Further benefits are observed with a longer pre-shear aging period or higher dosages (3–5%) of laponite.

The observed behavior is associated with reduced mobility of the sand particles during cyclic loading, which can be ascribed to two mechanisms: (1) bonding/bridging at the particle contacts due to the charged laponite fines which are attracted to the sand grains; and (2) formation of a pore fluid with solid like properties. The first appears to control the behavior with 1% laponite, while it is proposed that the second is responsible for the response with higher dosages of laponite.

The results presented provide new insight into the effects of high plastic fines on the cyclic response of sands, the “extreme” effects of the plasticity of the fines, and are significant in light of the possible use of laponite for liquefaction mitigation, an idea first put forth by the authors.

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1. Introduction

Pore pressures are fundamental to understand soil behavior, as in saturated soils they define effective stresses, which ultimately control the stress-strain-strength behavior of soils. In the context of earthquake geotechnical engineering, of particular significance is the generation of excess pore pressure that occurs in granular deposits due to ground shaking, as the accumulation of excess pore pressure and the decrease in effective stresses associated with this process can eventually lead to liquefaction, a phenomenon characterized by large deformations and in some cases catastrophic failure of structures on loose to medium granular deposits (e.g. [1–4]).

Cyclic behavior and pore pressure generation in granular soil deposits have been the object of extensive research, with efforts focused on the response of clean sands (e.g. [5–7]). However,

natural sand deposits present different amounts of fines and levels of cementation, encouraging the study of the effect of these variables on the cyclic behavior of sands (e.g. [8–11]).

Studies on the impact of non-plastic fines on the cyclic response and pore pressure development of sands present a wide variety of results (e.g. [12–16]). In contrast, it is fairly accepted that the presence of plastic fines (e.g. [2,17–20]) and cementation (e.g. [11,21]) increase the cyclic resistance of sands.

Recently, El Mohtar et al. [22,23] examined the effect of small percentages (3–5%) of bentonite on the cyclic resistance of sands. These clay percentages are at the low end of those examined by other researchers, and smaller than the threshold values that are thought to impact liquefaction resistance (e.g., in Youd et al. [24], the curve for fines content less than 5% is referred to as the “clean sand base curve”). The work by El Mohtar et al. [22,23], which was aimed at developing a method for improving the liquefaction resistance of granular soils, highlighted how amounts of bentonite as small as 3% by dry mass of the sand lead to an increase in the number of cycles to liquefaction of sand of over an order of magnitude. Moreover, the cyclic resistance continues to improve with continuous aging of the soil.

* Corresponding author.

E-mail addresses: fochoa@ing.uchile.cl (F. Ochoa-Cornejo), bbobet@purdue.edu (A. Bobet), cliffjohnston@purdue.edu (C.T. Johnston), mks@purdue.edu (M. Santagata), jvs@purdue.edu (J.V. Sinfield).

The work presented in this paper builds on this previous research and examines the effect of the presence of small percentages of laponite on the response of sands to cyclic shear. Laponite is a synthetic clay with particle diameter approximately ten times smaller than bentonite, and plasticity index of 1100%, significantly greater than that of bentonite, justifying its designation as a “super-plastic” clay.

Cyclic triaxial tests are conducted on specimens prepared mixing sand and 1% laponite (by dry mass of the sand) under dry conditions and subsequently saturated with water. Additional tests are conducted with dosages of 3% and 5% laponite. The response of these specimens is evaluated by comparison with clean sand specimens tested under similar conditions (skeleton relative density and cyclic stress ratio), with specific focus on the analysis of the excess pore pressure response. The paper carefully examines the generation of pore pressure during the various stages of cyclic loading, starting from the first loading cycle to the triggering of large strains, to the initiation of liquefaction.

As the presence of as little as 1% of laponite (by dry mass of the sand) is found to impact the cyclic response of the granular medium significantly, the tests on sand-laponite mixtures provide the means to examine the “extreme” effects of the plasticity of the fines.

Moreover, analysis of the results for different amounts of laponite and comparison to the existing database for sand-bentonite specimens [22,23] provide insight into the relative impact of the testing parameters (percentage and plasticity of the fines, and time). They also highlight how, depending on the nature and the fines content, different mechanisms may be responsible for the observed increase in cyclic strength.

Finally, the cyclic behavior of sand-laponite mixtures is also relevant to the potential use of laponite as an alternative to bentonite for treating liquefiable soils. This idea was first put forth by the authors' research team at Purdue University [25–27]. While bentonite is natural and safe, its application in the field presents some challenges related to (1) the chemical treatment with sodium pyro-phosphate required to control the short-term viscosity of bentonite dispersions to allow permeation in a porous medium [27]; (2) the inherent variability of this natural material, which can lead to inconsistent results; and (3) difficulties in permeating finer deposits. Laponite potentially overcomes these challenges due to its smaller size when fully dispersed, its consistent properties, and the delayed gelation properties of laponite dispersions. In this context, this research provides insight into the amount of laponite that might be necessary to deliver in a porous medium for improving its liquefaction resistance and the changes in engineering properties that might be anticipated.

2. Materials, equipment, and experimental procedures

2.1. Materials

As discussed in more detail below, the experimental program included undrained cyclic triaxial testing on cylindrical specimens prepared with clean Ottawa sand (C778) and mixtures of Ottawa sand and laponite.

Ottawa sand is a clean uniform ($C_u=1.48$) silica sand with particle size distribution in the fine-to-medium range (100–600 μm), and less than 1% fines. Ottawa sand particles have a rounded to sub-rounded shape, soft gray color and specific gravity (G_s) of 2.65. The maximum and minimum void ratios are $e_{\text{max}}=0.480$ and $e_{\text{min}}=0.783$ [28].

Laponite, $\text{Na}_{+0.7}[(\text{Si}_8\text{Mg}_{5.5}\text{Li}_{0.3})\text{O}_{20}(\text{OH})_4]_{-0.7}$, is a synthetic nanoclay similar to natural hectorite, which is used as a rheology modifier in a range of applications (e.g. cosmetics, inks, paints,

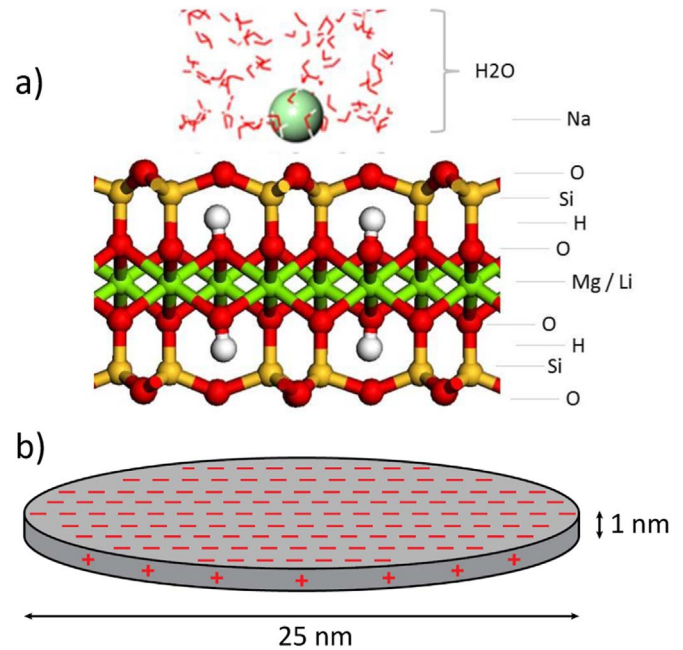


Fig. 1. a) Structure of laponite and b) geometry of individual laponite particle.

surface coatings, glazes). It is a 2:1 clay formed by a magnesium octahedral sheet sandwiched between two silica tetrahedral sheets (Fig. 1a). Isomorphous substitution of magnesium by lithium atoms generates negative charges on both faces, which are counterbalanced by interlayer cations, generally sodium. The rims have weaker pH dependent positive charge. Single laponite particles have a disk-like shape approximately 25 nm in diameter and 1 nm thickness (Fig. 1b) and specific gravity of 2.57; bentonite particles also have a fundamental thickness of 1 nm but the diameter is much greater than laponite (200–1000 nm). In dry form, laponite crystals form silt size stacks by sharing the interlayer sodium ions. When dispersed in water, laponite hydrates and swells, forming a clear, primarily monodisperse suspension, with behavior controlled by electrical interactions. Depending on the experimental conditions (clay concentration, pH, ionic strength) repulsive or attractive forces control the structure and the response of the dispersion (e.g. [29–32]).

As a result of the small particle size and its affinity for water, laponite has a plasticity index (PI) of approximately 1100% [25]. This PI is significantly greater than that of natural clays (e.g. for bentonite $PI \sim 350$, [23]).

Laponite dispersions have rheological properties – early Newtonian behavior and delayed gelation process (e.g. [29,32,33]) – that are very attractive from the standpoint of delivering this nano-clay into the subsurface. This aspect of behavior is not addressed in this paper, as the focus is on the cyclic response of specimens prepared mixing sand and laponite under dry conditions, and subsequently permeated with water.

Laponite is manufactured and commercialized by BYK Additives and Instruments (previously Rockwood Additives Inc.) in different grades. The general purpose grade, laponite RD, referred to as laponite, was used in this work. Laponite RD is the material most extensively documented in the literature.

2.2. Specimen preparation and testing procedures

Two triaxial apparatuses were used to perform the cyclic tests presented in this paper: the CKC system from Soil Testing Equipment (San Francisco, CA) and the STX-050 system from GCTS (Tempe, AZ).

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