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# Pilot-scale modeling of colloidal silica delivery to liquefiable sands

Murat Hamderi<sup>a,\*</sup>, Patricia M. Gallagher<sup>b</sup>

<sup>a</sup>Royal Haskoning DHV-ELC, Istanbul, Turkey

<sup>b</sup>Dept. of Civil, Architectural and Environmental Engineering, Drexel University, Philadelphia, PA, USA

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## Abstract

Passive site stabilization is a developing technology for the in situ mitigation of the risk of liquefaction without surface disruption. It involves the injection of stabilizing materials into liquefiable saturated sand. In this study, a pilot-scale facility (243 cm by 366 cm in plan × 122 cm deep) was used to inject a dilute colloidal silica stabilizer into liquefiable sand specimens. The grout advancement was monitored in real time using electrical conductivity cells embedded in the specimens. Injection rates ranging from 65 to 9000 ml/min/well were used to investigate the optimal rate of grout delivery. In tests with low injection rates, the delivery performance was low due to sinking, while at higher injection rates, sinking was less noticeable. After the treatment, the degree of grout penetration was evaluated by excavating the model. The in situ unconfined compressive strength was measured using a pocket penetrometer, and soil blocks were excavated for additional unconfined compressive testing. Moreover, the 3-D flood simulator, UTCHEM, was utilized to simulate the experimental results and to predict the injection rates for adequate stabilizer delivery. The results of the strength testing demonstrated that as little as 1% by weight of the colloidal silica provides a significant improvement in strength after a month of curing. The study also revealed the feasibility of delivering colloidal silica to liquefiable sands by implementing a large-scale treatment.

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**Keywords:** Chemical grouting; Soil liquefaction; UTCHEM; Colloidal silica; Chemical transport; Groundwater

## 1. Introduction

Passive site stabilization is a technique for the non-disruptive mitigation of the risk of liquefaction at developed sites susceptible to liquefaction. The stabilization is performed by slowly by injecting a stabilizing material at the up gradient edge of a site and delivering the stabilizer to the liquefiable area using the groundwater flow augmented by injection and extraction wells (Fig. 1). The stabilizer used for this technique is colloidal silica (CS), which is an aqueous dispersion of microscopic silica particles

that can be made to gel by adjusting the pH or ionic strength of the dispersion. Laboratory, bench scale, centrifuge and field tests have all demonstrated the effectiveness of the CS treatment against liquefaction and liquefaction-induced damage (e.g., Gallagher and Mitchell, 2002; Gallagher et al., 2007; Conlee et al., 2012). One feasibility issue remaining is the ability to deliver the CS uniformly over long distances. Gallagher and Lin (2009) demonstrated the ability to transport CS in adequate concentrations in 1-m, 3-m and 10-m-long one-dimensional column tests. Gallagher et al. (2007) successfully delivered CS to a 2-m-thick liquefiable zone over a 9-m-diameter test area.

The most difficult feasibility issue to address for passive site stabilization is whether the grout can be delivered uniformly to the liquefiable formation. In this research, we developed a pilot-scale box model to investigate the ability to deliver dilute

\*Corresponding author.

E-mail addresses: mhamderi@yahoo.com (M. Hamderi), pmg24@drexel.edu (P.M. Gallagher).

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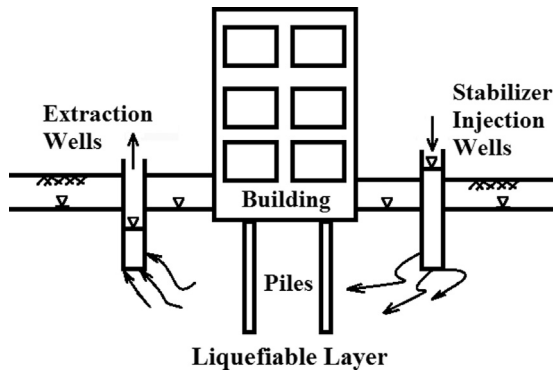


Fig. 1. Passive site stabilization concept.

CS in a large-scale laboratory model. This paper reports the results of pilot-scale injections in a 10-m<sup>3</sup> pilot-scale facility. In addition, we used UTCHEM, a finite difference numerical simulator that can account for various densities and viscosities, to model the results of experiments and to predict the optimal injection rates for adequate stabilizer delivery.

## 2. Colloidal silica properties and use in liquefaction mitigation

Colloidal silica (CS) is an aqueous dispersion of fine-sized, amorphous, nonporous and typically spherical silica particles in the liquid phase ranging from 5 to 100 nm in diameter (DuPont, 1997). During their manufacturing, CS solutions are stabilized with alkali solutions against gelation. Alkaline solutions make the nano particles ionize and repel each other. Gelation can be initiated by weakening the repulsive forces. This can be achieved by adjusting the pH level or the salt concentration. In most cases, adjusting the pH is cumbersome; therefore, the gelling time can usually be adjusted by only adding salt. In this study, Ludox-SM was selected from among the several types of CS available. Ludox-SM CS is a highly stable dispersion of 7-nm size SiO<sub>2</sub> particles. The dispersion has 30% SiO<sub>2</sub> by weight and a viscosity of about 5.5 mPa s at 20 °C. When CS is diluted to 6% with water, the density of the CS is about 1.035 g/cm<sup>3</sup> at 23 °C (density of tap water=0.995 g/cm<sup>3</sup> at 23 °C) and the initial viscosity is between 1.05 and 1.6 mPa s (viscosity of tap water=0.92 mPa s at 23 °C). The time to gelation can range from a few minutes to a few months (Gallagher and Mitchell, 2002). The general shape of the gel time curve is the same regardless of the gel time, as shown in Fig. 2, which presents the gel time curves for the experiments described later in this paper. The viscosity of the diluted CS remains low until just before gelation begins; this allows the grout to be injected for most of the induction period.

## 3. Previous studies on CS

### 3.1. Performance of CS in liquefaction mitigation

In the past fifteen years, numerous researchers have reported on significant improvements in the deformation resistance of

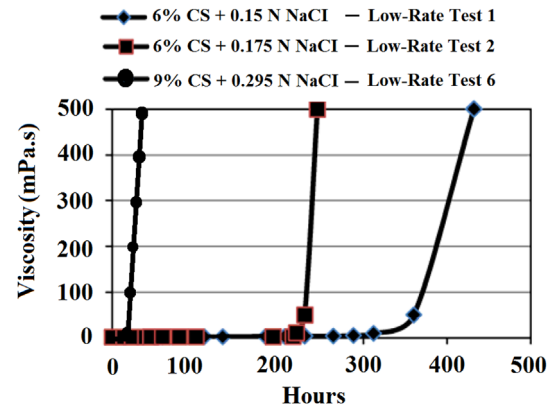


Fig. 2. Gel time curves of CS solutions used in this research.

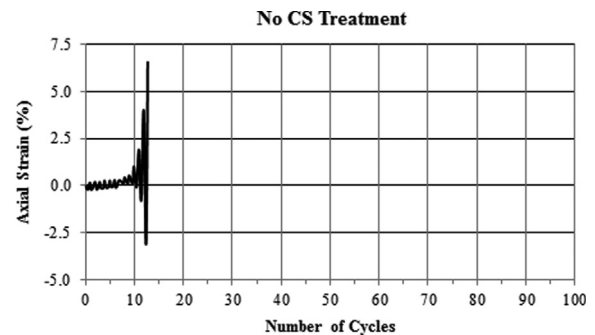


Fig. 3. Cyclic stress–strain behavior of untreated Monterey sand, relative density=22%, CSR=0.27 (Gallagher and Mitchell, 2002).

loose sands treated with CS in percentages from 2% by weight to 20% by weight (e.g., Kabashima and Towhata, 2000; Towhata and Kabashima, 2001; Gallagher and Mitchell, 2002). Loose sand treated with CS typically behaves similarly to dense sand and shows significant damping and cyclic mobility upon continued loading. Gallagher and Mitchell (2002) evaluated the performance of CS-treated and untreated samples by comparing their cyclic deformation resistance. The cylindrical Monterey sand samples were treated with 5% to 20% CS by weight. The samples were 7.5 cm in diameter by 15.9 cm in height. The Monterey sand had a  $d_{50}$  of 0.44 mm ( $d_{50}$  is the grain size corresponding to 50% passing). The void ratio of the samples was 0.70 which corresponded to a relative density value of 22%. The samples were compared in terms of strain development at a given CSR which is defined as the ratio of the maximum cyclic shear stress to the initial effective confining stress. A sinusoidal function with a period of 2 s was used for all tests. During the cyclic loading, untreated samples collapsed in 10–12 cycles (Fig. 3), whereas samples treated with 5% and 10% CS by weight could withstand at least 100 cycles, and they remained intact (Fig. 4a and b).

Conlee (2010) conducted a series of CS silica field injection tests to treat a 0.5-m-thick layer of poorly graded sand with silt against liquefaction. The injection was performed in a 9 m<sup>2</sup> area with an average injection rate of 5.7 l/min. Following the treatment, some dynamic shaking was introduced with dynamic shaker TRex. The induced accelerations ranged from 0.05 g to

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