The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Effects of high-diluted colloidal silica grout on the mechanical behavior of a liquefiable sand

G. Ciardi, R. Bardotti, G. Vannucchi & C. Madiai
Universita degli Studi di Firenze, Firenze, Italy

ABSTRACT: It has recently been demonstrated that colloidal silica (CS) can be successfully used to stabilize liquefiable soils. However, the effects of high-diluted CS mixtures have not been exhaustively investigated yet. This paper presents the results of an experimental testing campaign pointing out how CS dilution modifies the mechanical properties of a liquefiable sand. Cyclic and monotonic triaxial tests for untreated sand, as well as for sand treated with different CS contents, were carried out. Oedometer tests were performed to explore additional effects of the CS treatment on soil properties. The effects of a 5% CS by weight concentration were evaluated and taken as the reference for comparison with the results of previous studies. Furthermore, different CS contents, lower than 5% CS by weight, were used to prepare stabilized specimens. As a result, experimental evidence revealed that these dilutions can also be used to improve the behavior of the material against liquefaction.

1 INTRODUCTION

Seismic liquefaction of saturated cohesionless soils represents one of the most catastrophic effects of earthquakes of a certain size. It occurs as a result of the build-up of pore water pressure under undrained loading conditions; the soil shear strength is reduced, and it can possibly reach zero value. A systematic scientific interest toward liquefaction has come out following the dramatic damages reported after Niigata (Japan) and Alaska Earthquakes (1964); more recently, several liquefaction occurrences have been recorded after e.g. Taiwan (1999), Christchurch (2011, New Zealand), Emilia (2012, Italy) and Hokkaido (2018, Japan) Earthquakes.

Historically, a great variety of remedial measures against liquefaction have been developed over the past years, with the aim of improving the liquefaction resistance of liquefiable soil deposits. The most traditionally used techniques are fundamentally based on the improvement of the mechanical properties of the soil mass by increasing the soil density (e.g. sand compaction pile, vibro-flotation, dynamic tamping), by means of grain solidification (e.g. injection methods, deep mixing), by the lowering of the ground water table or through a reduction of the earthquake-induced pore water pressure (e.g. dewatering by trenches, drains, partial saturation), or by means of grain adjustment (e.g. soil replacement); a combination of different techniques could be required to face the liquefaction risk at a specific site.

The injection of colloidal silica (CS) grout into liquefiable sands promises to be an innovative way to chemically stabilize a liquefiable deposit (Gallagher et al. 2007). A colloidal silica solution is a stable, harmless, low-viscosity aqueous dispersion of colloidal silica particles that can be destabilized by properly mixing it with a reactant, like an electrolyte. This destabilization essentially takes place as a result of the decrease of the repulsive forces acting on silica particles, and it is characterized by the formation of siloxane bonds (Si-O-Si) resulting in an increase of viscosity and in the development of a gelled matrix. If the chemical gelation process occurs into the soil matrix, the sand grains are provided with a sort of cohesion, thus binding the grains. Consequently, the sand liquefaction resistance also increases (e.g. Gallagher & Mitchell 2002, Diaz-Rodriguez et al. 2008, Porcino et al. 2012, Vranna & Tika 2015). The strength of the gel pattern is related to the initial silica contents of the grout (Cao et al. 2010): the higher the silica contents, the higher the level of soil improvement. For instance, the unconfined compressive strength (UCS) of the treated sand increases with the increase of CS contents and of the time after which the test is performed (e.g. Gallagher & Mitchell, 2002; Liao et al. 2003; Mollamahmutoglu & Ylmaz 2010). The gelation process (the rate of viscosity increase) can be controlled by managing several parameters of the grout solution, such as its ionic strength, pH, temperature, particle size, and silica solids contents (Iler 1979); understanding the rheological properties of the material is essential for a proper site design (Pedrotti et al. 2017).

As suggested by Gallagher & Mitchell (2002), a 5% by weight of colloidal silica concentration in the grout solution is a good compromise between the attained increase of sand liquefaction resistance and the economic cost of the treatment. The majority of the researchers who worked on this topic used CS contents no lower than 5%; however, it was found that even silica concentration lower than 5% may provide the soil with an adequate improvement (Kodaka et al. 2005, Hamderi & Gallagher 2015). The main goal of this study is to evaluate the effects of high- diluted (<5% by weight) colloidal silica treatment on the mechanical properties of a potentially liquefiable sand by means of laboratory testing, in order to reduce costs for practical application. The experimental testing campaign included monotonic as well as cyclic triaxial tests, and oedometer tests on treated and untreated material. The results of these laboratory investigations are herein presented and discussed.

2 EXPERIMENTAL TESTING

2.1 *Materials and methods*

The tested soil consisted of a clean, uniform, mainly siliceous sand, named S3 sand; it is obtained by sieving a commercial sand, extracted from the Fossanova quarry (Italy) and named FO-25 sand, between the sieves #40 and #80 (ASTM D422-63 series). It has subrounded, low-sphericity grains and specific gravity G_s = 2.65. It is characterized by a grain distribution that well matches those indicated for most liquefiable sands, with uniformity coefficient D_{60}/D_{10} = 1.6 and mean particle diameter D_{50} = 0.30 mm. Maximum and minimum void ratios are equal to e_{max} = 0.839 and e_{min} = 0.559 respectively (DIN 18126:1996-11).

MasterRoc® MP 325 (BASF) colloidal silica was selected for the soil treatment in this study. It is supplied as a 15% (by weight) SiO_2 solution, with a viscosity of approximately 10 mPas, a density of 1.1 kg/L and a pH of 10 at 20°C. Gelling of CS solution is induced by adding to it a certain amount of a reactant, which consists of a saline solution made of distilled water and sodium chloride (10% by weight NaCl solution). This reactant is referred to as the accelerant in this paper. The grout solution used in this study was finally made up of CS solution, accelerant and distilled water. The CS contents are intended as the percentage of silica solids in the grout solution, by weight.

Treated and untreated materials were tested: monotonic and cyclic triaxial tests were carried out on treated and untreated sand, as well as oedometer tests. Tests on treated material were performed after a fixed curing time, that is here defined as the time between the gel formation and the testing time of the specimens.

2.2 *Preliminary tests*

Two sets of preliminary experiments were carried out. Firstly, gel time was evaluated empirically by preparing several grout solutions with different ratios between CS contents and the amount of accelerant; the solutions, of equal total volume, were then poured into glasses and they gelled at constant room temperature. The gel time was determined as the time between the mixing of CS and reactant and the time at which less than approximately 10% of the mixture flew along the glass after its rotation of 90°. Different CS contents were used: 1%, 2% and 5%. No gel was detected for 1% CS concentration after 21 days of curing time; it is thought that such low concentration may be unfeasible for in field practical applications, and for this reason it was not further tested. The *2%* CS contents gel can be visually described as a “weak” gel: the gelled matrix was not as firm as those resulting from the higher CS contents tested.

Secondly, in order to choose a proper curing time for laboratory testing, a set of grouted sand specimens was prepared, for each CS concentration value, by pluviating a fixed weight of dry sand into glasses containing the same grout amount; the ratio between the CS contents and the amount of accelerant (by volume) was set to allow a gel time of 120 min for the whole set of specimens. After pluviation, the top of the glasses was carefully sealed with a plastic film, to avoid any evaporation. Pocket penetrometer tests were carried out on treated specimens after different curing times, ranging from 1 up to 14 days: the undrained maximum strength was found to increase (with a power law) over curing time, consistently with data from previous research. Since more than 80% of the pocket penetrometer maximum strength was available after 5 days from gelation, these were assumed as curing time.

Therefore, in this study, all tests were performed by keeping constant gel time and curing time (120 min and 5 days, respectively), to ensure that all gelled specimens, treated with different CS contents grouts, were in the same initial conditions (i.e. the gel strength only depended on CS concentrations) when tested.

2.3 *Oedometer tests*

1D compressibility tests were performed on treated and untreated material. The specimens were prepared by pluviating dry sand into the steel ring of the oedometer, or by pluviating dry sand into the grout, within the ring, for untreated and treated samples respectively. The latter were prepared outside the oedometer chamber and carefully put in place after curing time; the untreated sample was directly prepared in the oedometer cell. Once the specimens were in the cell, a small load (approximately 10 kPa) was applied before the cell was filled with distilled and deaired water. The load sequence started 24h after the water was added; each load and unload step was kept for 24h.

2.4 *Triaxial tests*

Cylindrical specimens (100 mm height, 50 mm diameter) were used for triaxial tests. For untreated sand subjected to both monotonic and cyclic loadings, wet pluviation technique was used to prepare loose saturated samples. Dry sand was poured with the aid of a funnel into a split mold partly filled with distilled and deaired water. A rubber membrane was firstly stretched along the mold by applying a vacuum between them; then, the specimen preparation took place on the pedestal of the triaxial cell. After the mold was removed, the specimen dimensions were carefully measured and the triaxial cell was assembled and filled with distilled and deaired water. A sufficient degree of saturation (Skempton's coefficient $B > 0.95$) was achieved by back pressure increments.

Loose samples of treated sand were prepared outside the triaxial chamber, to prevent any contact between the pressure transducers and the grout. Plastic pedestals and top caps were designed and manufactured to allow a preparation identical to that of the untreated sand, but at the same time to avoid any possible risk for the pore water pressure transducers, which could be damaged by the contact with grouts. Dry sand was poured into the mold containing the grout solution with the aid of a funnel; the material was always kept below the grout level, to ensure full saturation. After preparation, the samples were sealed by means of valves and left to cure at constant room temperature. Each specimen was then moved to the triaxial cell, that was filled with distilled and deaired water after the specimen dimensions were recorded. To avoid bonds breakage due to back pressurization, no saturation phase was performed; because of the preparation procedure used, the specimens can be considered saturated.

Before monotonic shearing, the specimens were isotropically consolidated to an initial effective consolidation stress, σ_c', of 50, 100, 200 and 300 kPa. Drained and undrained monotonic tests, for untreated and treated sand respectively, were run by applying an axial compression load at a constant strain rate of 5.0% per hour; the pore water pressure was not recorded during the tests of treated material. Cyclic undrained triaxial tests were performed on samples isotropically consolidated at $\sigma_c' = 100$ kPa by applying sinusoidal loads at a frequency of 0.1 Hz. The failure condition under monotonic loading, for treated and untreated specimens, was assumed at the maximum value of $q = (\sigma_1 - \sigma_3)$ (being σ_1 and σ_3 the major and minor principal stresses) achieved during the test; the failure condition for treated sand under cyclic loading was assumed at ε_a = 5% (double amplitude axial strain). On the other hand, for untreated sand, the occurrence of ε_a = 5% or r_u = 1 corresponds to failure, being r_u the ratio between the excess pore water pressure Δu and σ_c'.

3 RESULTS

The results of oedometer, monotonic and cyclic triaxial tests are presented below, both for untreated sand and for treated one at 2% and 5% CS.

3.1 *Oedometer tests*

The results of oedometer tests on treated and untreated sand are shown in Figure 1. Vertical strain, ε_v, is plotted versus the normal effective consolidation stress, σ_v' (log-scale). As CS contents increase, the vertical strain increases for a given value of σ_v'. The maximum ε_v for 5% CS treated specimens is over three times the corresponding strain of the untreated sand. The increased compressibility of treated material versus that of untreated sand is consistent with data (Georgiannou et al. 2017) and it can be attributed to the presence of gelled silica, that would facilitate grain rearrangement under 1D loading. The gelled matrix, in fact, acts as a sort of buffer among the solid skeleton, and it helps the slip among the grains.

Since silica gel is compressible (Towhata 2008, Wong et al. 2018), the greater increase of vertical strain, $\Delta\varepsilon_v$, in treated material (compared with that of the untreated one), for a given value of $\Delta\sigma_v$', surely represents a critical issue for a practical use of CS treatment. The results obtained in this study could depend on three factors: on the specimens preparation method, on the CS contents used, on the sand characteristics. Wong et al. (2018) found that, although they measured the compressibility of pure silica gel, treated sand experienced less strain than that of the untreated one after oedometer tests. They prepared the specimen firstly by pouring dry sand into the oedometer ring, secondly by pouring CS grout from the top of the sample by means of a syringe. However, they used a significantly different material (D_{60}/D_{10} = 1.26, D_{50} = 1.20 mm) treated with very high CS contents (34% by weight) and packed with lower initial void ratio.

In Figure 2 the results of monotonic triaxial tests on treated and untreated sand are reported; the stress-strain relationships are provided for 2% and 5% CS grouted specimens compared with those of untreated ones for different values of Oc'. It can be observed that the

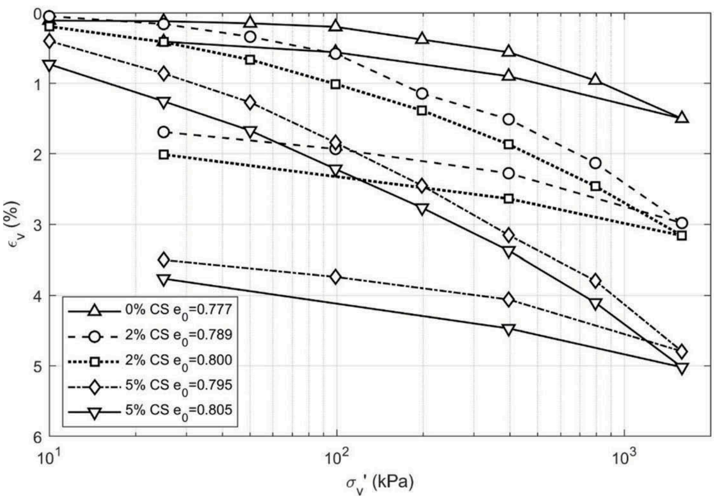

Figure 1. Oedometer tests results on treated and untreated materials.

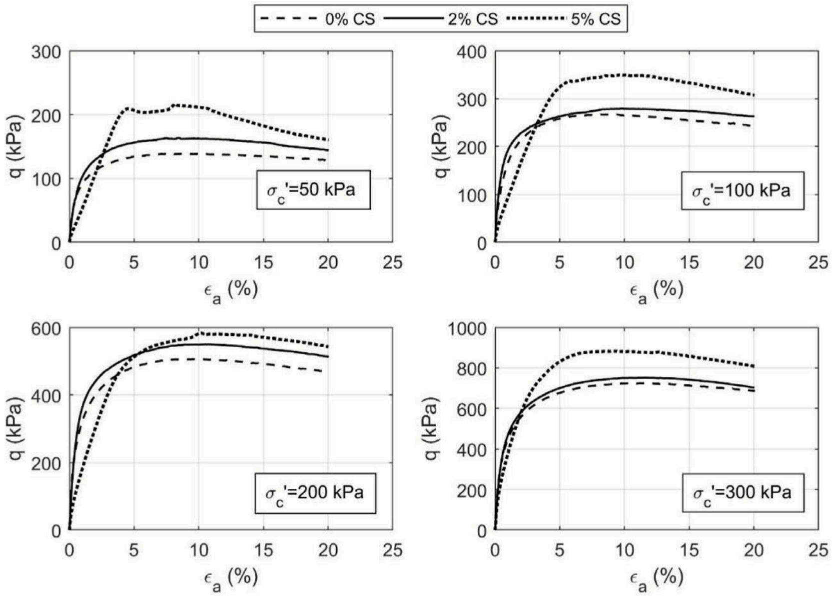

Figure 2. Deviatoric stress versus axial strain for treated and untreated samples from triaxial tests performed at different confining pressures σ_c'.

maximum value of q for treated sand is higher than that of untreated sand for a given Oc'. This trend, that indicates an increased peak resistance for treated sand compared to untreated material was observed for all the investigated concentrations, and it is consistent with previous works on higher silica concentrations (e.g. Georgiannou et al. 2017, Nouri Delavar & Noorzad 2017). Furthermore, the higher the CS contents, the higher the peak deviatoric stress of treated material over the entire range of consolidation stress.

However, in general agreement with the results of the oedometer tests, it can be seen that the presence of gel affects the stress-strain behavior of treated sand also under triaxial compression loading conditions. For treated material, the stiffness (tangent modulus) for strain levels smaller than 2% is much lower than that of the untreated one as silica contents increase; this fact is due to the presence of gel, that increases the grain rearrangement under triaxial loading condition. In Figure 3 the ratio between stiffness (calculated as the slope of the stress-strain curve for each 0.1% axial strain minor than 2%) of samples treated with a x% CS grout solution, E_x, and that of the untreated one, E_0, is plotted versus the axial strain in the range $0 < \varepsilon_a < 2\%$. It is shown that the stiffness of 5% CS treated sand is significantly different from that of 2% CS treated and untreated one. While for 2% treated sand the E_x values are close to E_0 and negligible variation is revealed in the whole range of ε_a considered, the values of E_x/E_0 for 5% CS grouted sand increase with the axial strain, thus indicating that the development of peak shear resistance is delayed and slower than for untreated sand.

The maximum shear stress at failure for treated and untreated materials is plotted in Figure 4 against the effective consolidation stress. It is shown that, for a given value of σ_c', the shear resistance of sand increases as CS contents increase. Within the investigated range of consolidation stresses, the higher the CS contents, the higher the level of improvement. It is noteworthy that the curves fitting the experimental data are almost parallel: it can be stated that the main responsible for the improved mechanical behavior of treated sand under monotonic loading could be a sort of "artificial" cohesion that the treated material is provided with. This hypothesis is consistent with other data from literature (Porcino et al. 2012, Vranna & Tika 2015); however, it is here shown that also a high-diluted 2% CS grout can bind the sand grains.

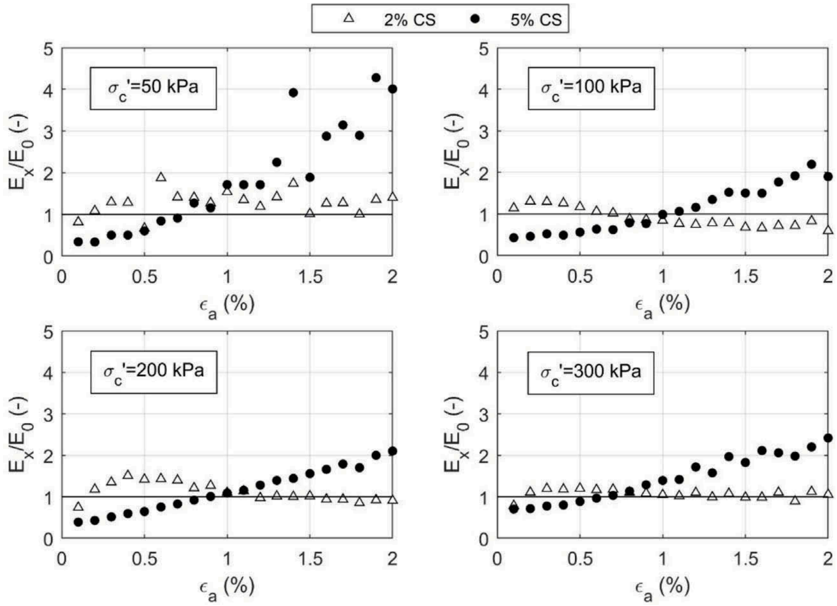

Figure 3. Ratio between the stiffness (tangent modulus) of treated (E_x) and untreated (E_0) materials against the axial strain from triaxial tests performed at different confining pressures σ_c'.

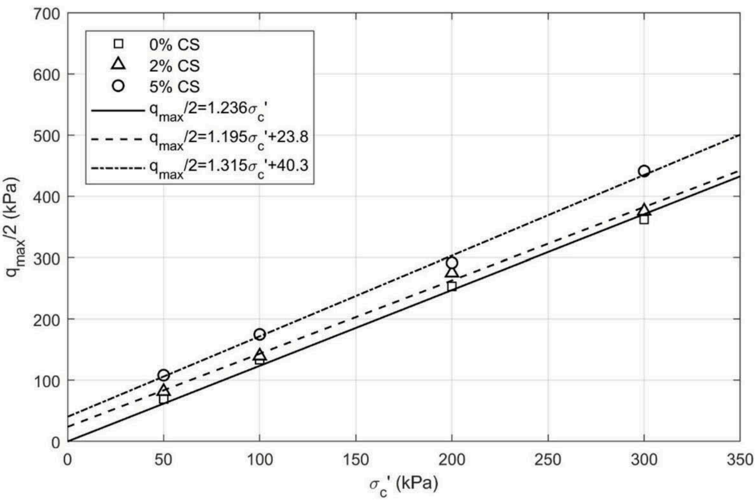

Figure 4. Maximum shear stress at failure against effective consolidation stress for treated and untreated materials.

3.3 *Cyclic triaxial tests*

The results of undrained cyclic triaxial tests are shown in Figure 5. The cyclic stress ratio CSR = $q/2\sigma_c$' is plotted versus the number of cycles to failure, N; no failure is assumed for N > 100. It is clearly shown that the liquefaction resistance of treated material is higher than that of clean sand, and, moreover, that a significant improvement is obtained also for 2% CS treated sand. The value of CSR corresponding to N > 100 increases as CS contents increase. It is confirmed that 5% CS grout is able to improve the liquefaction resistance of a clean sand (e.g.

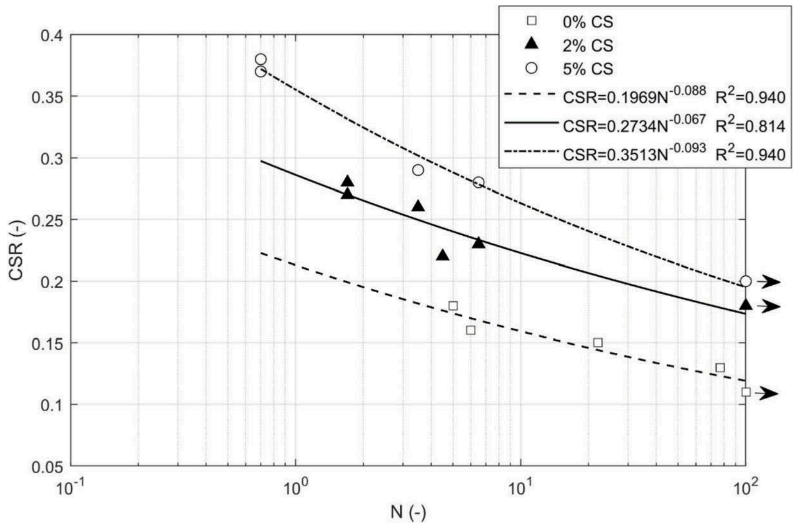

Figure 5. Failure curves for treated and untreated materials from cyclic triaxial tests.

Gallagher & Mitchell 2002), but it can be stated that 2% CS grout can also be used to improve the behavior of sand under cyclic loading conditions.

4 CONCLUSIONS

In this paper, the effects of colloidal silica mixtures on the mechanical response of a liquefiable clean sand were investigated.

The effects of a 5% CS by weight concentration were evaluated for the comparison with the results of previous studies and a general agreement with those was observed. Different CS contents, lower than 5% CS by weight, namely 1% and 2%, were used to prepare stabilized specimens. Since no firm gel was detected for 1% CS concentration after 21 days curing time, this low concentration was considered unfeasible for in field practical applications.

Laboratory tests performed on 2% CS treated sand showed that 2% CS grout is enough to improve the behavior of the material under both monotonic and cyclic loading conditions. While theresistance under static and cyclic loading conditions increases with CS contents, however, the grouted sand compressibility under 1D loading conditions increases too.

After 1D compression tests, the 2% CS treated sand exhibited higher strain if compared to that of untreated material, but lower if compared tothat of sand treated with greater CS contents. Under monotonic loading, the 2% CS treated sand exhibited a stiffer response, similar to that of natural sand, if compared to that of 5% CS treated material, over the whole range of the considered confining pressures; the peak shear resistance was also higher than that of unimproved material. Under cyclic loading, given a certain stress level, the number of cycles needed to reach failure was significantly higher for treated sand than forthe natural one.

In conclusion, despite the benefits in terms of increased shear resistance and improved behavior against cyclic loading of both 2% and 5%CS treated material, the ability of 2% CS grout to improve the mechanical properties of a liquefiable sand can lead to greatsavings for in field practical ground improvement treatments without significantly affecting the stiffness of the treated soil at small strain levels.

ACKNOWLEDGEMENTS

This study was supported by DPC-ReLUIS Research Project 2018.

REFERENCES

ASTM D422-63(2007)e2. Standard Test Method for Particle-Size Analysis of Soils (Withdrawn 2016), ASTM International, West Conshohocken, PA, 2007.

Cao, X., Cummins, H.Z., & Morris, J.F. 2010. Structural and rheological evolution of silica nanoparticle gels. Soft Matter 6(21): 5425–5433.

DIN 18126 (1996-11). Baugrund, Untersuchung von Bodenproben - Bestimmung der Dichtenichtbindiger Böden bei lockerster und dichtester Lagerung. Berlin: Beuth.

Díaz-Rodríguez, J.A., Antonio-Izarraras, V.M., Bandini, P., & López-Molina, J.A. 2008. Cyclic strength of a natural liquefiable sand stabilized with colloidal silica grout. Canadian Geotechnical Journal 45 (10): 1345–1355.

Gallagher, P.M., Conlee, C.T., & Rollins, K.M. 2007. Full-scale_field testing of colloidal silica grouting for mitigation of liquefaction risk. Journal of Geotechnical and Geoenvironmental Engineering 133 (2): 186–196.

Gallagher, P.M. & Mitchell, J.K. 2002. Influence of colloidal silica grout on liquefaction potential and cyclic undrained behavior of loose sand. Soil Dynamics and Earthquake Engineering 22(9): 1017–1026.

Georgiannou, V.N., Pavlopoulou, E.-M., & Bikos, Z. 2017. Mechanical behaviour of sand stabilised with colloidal silica. Geotechnical Research 4(1):1–11.

Hamderi, M. & Gallagher, P.M. 2015. Pilot-scale modeling of colloidal silica delivery to liquefiable sands. Soils and Foundations 55(1):143–153.

Iler, K.R. 1979. The chemistry of silica. New York: John Wiley and Sons Inc.

Kodaka, T., Ohno, Y., & Takyu, T. 2005. Cyclic shear characteristics of treated sand with colloidal silica grout. In Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering 16: 401–404. Rotterdam: Balkema.

Liao, H.J., Huang, C.C., & Chao, B.S. 2003. Liquefaction resistance of a colloid silica grouted sand. In Grouting and ground treatment 1305–1313.

Mollamahmutoglu, M. & Yilmaz, Y. 2010. Pre-and post-cyclic loading strength of silica grouted sand. In Proceedings of the Institution of Civil Engineers-Geotechnical Engineering 163(6): 343–348.

Nouri Delavar, I. & Noorzad, R. 2017. Drained shear strength parameters of silty sand grouted by colloidal silica. International Journal of Geotechnical Engineering 1–8.

Pedrotti, M., Wong, C., El Mountassir, G., & Lunn, R.J. 2017. An analytical model for the control of silica grout penetration in natural groundwater systems. Tunnelling and Underground Space Technology 70: 105–113.

Porcino, D., Marcianò, V., & Granata, R. 2012. Static and dynamic properties of a lightly cemented silicate-grouted sand. Canadian Geotechnical Journal 49(10): 1117–1133.

Towhata, I. 2008. Geotechnical Earthquake Engineering. Berlin: Springer Science & Business Media.

Vranna, A. & Tika, T. 2015. Undrained monotonic and cyclic behaviour of a silty sand stabilized with colloidal silica. In 6th International Conference on Earthquake Geotechnical Engineering Christchurch, NZ.

Wong, C., Pedrotti, M., El Mountassir, G., & Lunn, R.J. 2018. A study on the mechanical interaction betweensoil and colloidalsilica gel for ground improvement. Engineering Geology 243:84–100.