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EFFECTS OF COLLOIDAL SILICA GROUTING ON THE DYNAMIC PROPERTIES OF SANDY SOILS

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ABSTRACT

Results of resonant column tests (shear modulus and damping ratio) on reconstituted specimens of clean sands and silty sands impregnated with aqueous solutions of colloidal silica of varying concentrations are presented. Colloidal silica solutions are used as grouting material for stabilizing liquefiable soils and are characterized by several advantages when compared to other chemical grouts. The torsional resonant column tests were performed on specimens of clean or silty sand impregnated with solutions having two different colloidal silica concentrations. The test results of treated material were compared to relevant results of untreated ones, and the effects of: fines content (0% and 10%), relative density (30% and 50%), confining pressure (50kPa to 300kPa) and shear strain (10^{-5} to 10^{-3}) were studied. The results of tests indicate that the treated specimens are characterized by increased values of shear modulus and damping ratios, especially for loose conditions, small shear strains and high confining pressures. In terms of modulus increase the efficiency ranges from 55% to 65% whereas the damping ratio increases from 0% to 55%, for clean sands and from 0% to 25% for silty sands. The increase of relative density results in a higher efficiency for shear modulus; for the damping ratio, however, the opposite effect is observed, i.e. a reduction of efficiency. The presence of fines lowers, in general, the efficiency of grouting. Furthermore, the efficiency of the particular grouting material remains satisfactory even for low values of colloidal silica concentrations.

Keywords: Passive soil stabilization; colloidal silica; resonant column testing; liquefaction mitigation

1. INTRODUCTION

The use of chemical grouting for stabilization of sandy soils against liquefaction has been a subject of geotechnical experimentation since the 1980's (pertinent literature appears in Porcino et al., 2012) and the efficiency of a number of grouting materials has been tested, including: cement, microfine cement, sodium silicate and mineral grouts (Phan, 2014).

A type of grouting material that has attracted the interest of researchers since the 1990's is the aqueous solutions of colloidal silica (Agapoulaki et al., 2015), which – through laboratory element, pilot scale testing and centrifuge experiments - have been found to inhibit the occurrence of liquefaction and lateral spreading when injected to the subsoil through the ground water flow (Noll et al., 1993; Towhata and Kabashima, 2001; Gallagher and Mitchell, 2002; Liao et al., 2003; Thevanayagan and Jia, 2003; Pamuk et al., 2007; Gallagher et al. 2007 a, b; Diaz-Rodriguez et al., 2008; Spencer et al., 2008; Gallagher and Lin, 2009; Conlee, 2010; Porcino et al., 2012; Hamderi and Gallagher, 2015; Georgianou et al., 2017). The computational modeling of the behavior of grouted soil has also been the subject of recent research efforts (Papadimitriou et al., 2014; Andrianopoulos et al., 2015, 2016). The technique is known as "passive stabilization" and has the advantage that can be applied under existing structures supported by shallow or piled foundations. It involves a slow injection of stabilizer-enriched pore fluid with time-increasing viscosity, at the upgradient side of an existing structure

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followed by delivery under the structure via ground water flow, Figure 1. The advantages of the passive stabilization method, against other chemical grouting techniques, are that the grouting material (1) has the required initial liquidity for impregnation of both sands and silty sands, (2) its viscosity increases with time (depending on the pH of solution), transforming the initially liquid grout to a gel, which does not allow any pore water increase or the development of large deformations, (3) can be applied under existing structures, (4) is free of any biological or chemical environmental effects, (5) there are no adverse effects on soil structure and on the overlying construction, (6) it requires mobilization of small size equipment and facilitates access to the interior, and (7) has a low cost.

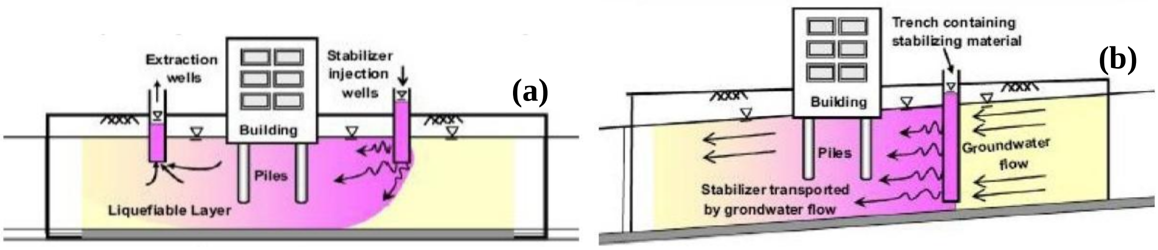

Figure 1. Concept of passive stabilization: (a) augmented flow, (b) natural groundwater flow (from Pamuk et al., 2007)

This paper presents the results of an experimental program, involving torsional resonant column tests on saturated specimens of a clean sand (M31/0) and a silty sand with 10% fines content (M31/10) impregnated with solutions of silica colloids having concentration CS=10% and CS=6%, for evaluating the dynamic properties (shear modulus and damping ratio) of the grouted material. The testing program is part of a broader research effort for developing soil liquefaction prevention methods under existing structures using environmentally friendly grouts consisting of silica colloids (nanomaterials). The results of tests on impregnated specimens are compared to corresponding results on non-impregnated material and conclusions are drawn regarding the amount of improvement and its dependence on (1) fines content of the ground, (2) confining pressure and, (3) magnitude of the imposed shear strain.

2. MATERIALS AND TEST PROCEDURES

Commercially available colloidal silica (Ludox-SM) was used in the experimental program (DuPont, 1997). The particular type was selected based on the fact that (a) it is the preferred one for passive stabilization applications, (b) has the smallest particle size (7mm) and the largest specific surface ($345m^2/gr$), and (c) smaller quantities per unit weight are needed to became gel, thus being the most economical selection.

The sands used in the tests were selected considering the types of natural liquefiable soils that are candidate for applying the method of passive stabilization as well the types of soils that have been used in similar laboratory studies (Persoff et al., 1999; Gallagher P., 2000; Koch, 2002; Kodaka et al., 2005; Lin, 2006; Pamuk et al., 2007; Spencer et al., 2008; Diaz-Rodriguez et al, 2008). Based on the above criteria two quartz sands were selected: a uniform clean sand with medium granulometry (denoted by M31/0) and a silty sand with 10% fines content (M31/10). Both sands have similar grain size (D_{50}=0.27-0.30mm), but different uniformity coefficients, C_u (1.3 for M31/0 and 4.0 for M31/10).

The impregnation of test specimens with silica solutions was performed with a system designed and fabricated in the Laboratory of Geotechnical Engineering, Dept of Civil Engineering, University of Patras, for the needs of the research project, following the provisions of ASTM D4320, Figure 2a. Similar systems have been used in the past for investigating the efficiency of different types of grouting (Vipulanandan and Shenoy, 1992; Markou and Atmatzidis, 2002; Pantazopoulos et al., 2012). The use of the particular system makes possible (a) the preparation of impregnated soil specimens under conditions similar to the field applications of injection grouting, and (b) the production of specimens that are ready for testing, with no need for cutting or/and trimming which could induce specimen disturbance. The impregnation procedure involved the following successive stages: (a) formation, by pluviation, of the sand (or silty sand) specimen with the desired void ratio (or relative density) in a cylindrical plastic split-type mold (the top and bottom of specimen were covered with perforated cups to prevent the loss of soil particles) / saturation of specimen by imposing low velocity flow of distilled water directed against gravity, (b) preparation of the colloidal silica solution with the selected silica concentration (6% and 10%) / placement of the solution in the grout reservoir / injection of the grout solution from the bottom to the top into the specimen under the minimum required pressure / the injection was continued until a volume of grout equal to twice the volume of specimen voids had been injected to ensure the complete impregnation of specimen, and (c) the input and output valves of the mold were closed and the grouted specimen was left to cure for a period equal to four times the gel time of the solution, in order to obtain the necessary stiffness before being transferred to the resonant column apparatus. In the present study the gel time of the solution was taken to be equal to 48hrs based on experimental results reported by Agapoulaki and Papadimitriou (2015). A photo of a treated specimen mounted in the resonant column device is shown in Figure 2b.

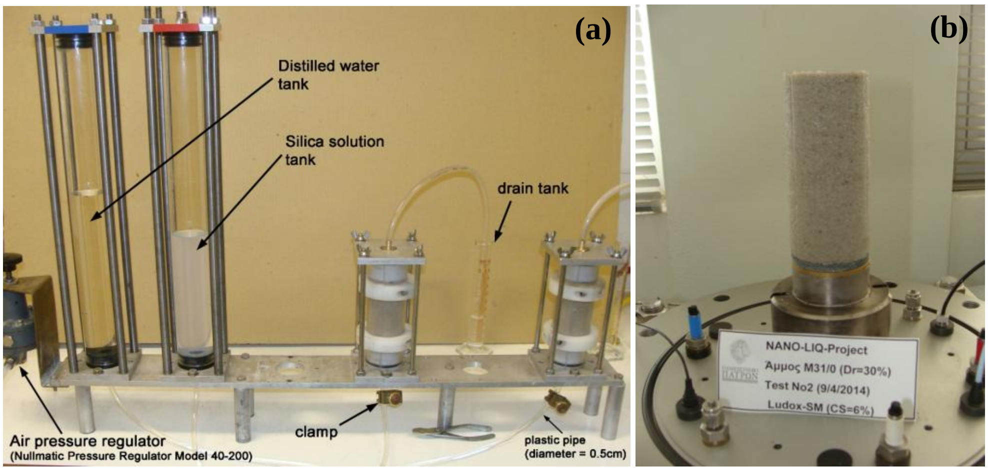

Figure 2. (a) Laboratory system for impregnating sandy specimens, (b) Treated specimen of sand

The resonant column tests in the present investigation were performed using the GDS RCA apparatus, Figure 3, following the standard procedure described in ASTM D4015. More detailed information on the aforementioned equipment can be found in (Pantazopoulos and Atmatzidis, 2012). The tests were performed utilizing the torsional mode of specimen vibration on cylindrical specimens with a diameter of 50mm and height equal to 110mm. The tests were conducted under isotropic confining pressures of 50, 100, 200 and 400kPa.

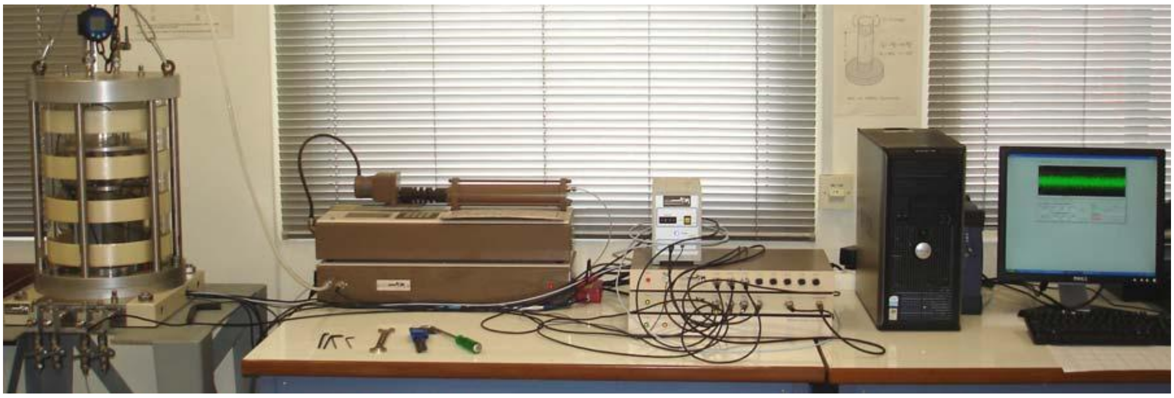

Figure 3. GDS Resonant Column System (GDS RCA).

3. RESULTS OF RESONANT COLUMN TESTS

3.1 Behavior of ungrouted sands

Reference values of dynamic properties (shear modulus, G, and damping ratio, D) were obtained by testing specimens of clean sand (M31/0) and silty sand (M31/10) in a loose condition (D_r=30%, e=0.73) and medium dense condition (D_r=50%, e=0.7). The combined effects of relative density and shear strain are shown in the plot of Figure 4. The diagrams indicate that the shear modulus of silty sand is reduced by 25% compared to clean sand, for both the loose and the medium dense of soil material. Furthermore, this reduction of stiffness is less pronounced for higher values of shear strains. In contrast to the above behavior, the test results indicate that the damping ratio is insensitive to the silt content, for shear strains up to $3*10^{-4}$.

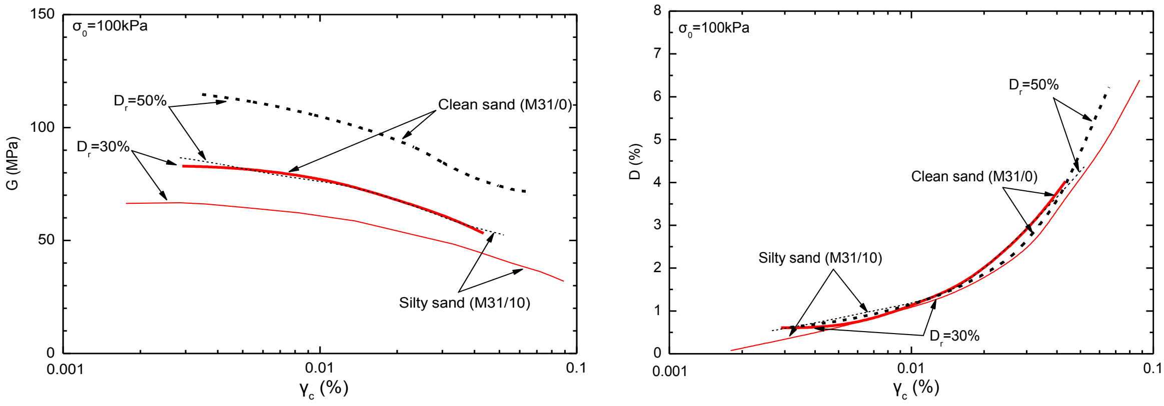

Figure 4. Behavior of clean sand (M31/0) vs. silty sand (M31/10)

3.2 Behavior of grouted sands

The test results for impregnated specimens with a solution concentration of CS=10%, for both clean sand and silty sand (for loose and medium dense conditions) are presented in the diagrams of Figure 5. It is observed that for the case of clean sand the shear modulus increases from 20% (loose condition, medium strains, $\gamma_c \approx 10^{-3}$ and high values of confinement σ_0=300kPa) to 65% (loose condition, small strains, $\gamma_c \approx 10^{-5}$ and high values of confinement σ_0=300kPa). Similar increases of shear modulus for loose clean sands treated with colloidal silica solutions have been reported on the basis of resonant column test results (Spencer et al., 2008) and of centrifuge tests (Conlee, 2010). Regarding the damping ratio of the materials it is observed that the increase of its value ranges from negligible (medium dense condition, medium strains $\gamma_c \approx 10^{-4}$ and high confinement σ_0=300kPa) to 55% (for loose condition, medium strains $\gamma_c \approx 10^{-4}$ and small values of confining pressure, σ_0=100kPa).

The tests results for the case of silty sand are shown in Figure 6, indicating that the shear modulus increase due to grouting, varies from 55% (for dense conditions, small strains $\gamma_c \approx 10^{-5}$ and large values of confining stress, σ_0=300kPa) to 100% (for loose conditions, small strains $\gamma_c \approx 10^{-5}$, and large confining pressure). On the other hand, a damping ratio increase is observed, which is negligible (for dense condition, medium strains, $\gamma_c \approx 10^{-4}$ and high values of confinement, σ_0=300kPa) and reaches 25% (for loose soil, medium strains, $\gamma_c \approx 10^{-4}$ and low values of confinement, σ_0=100kPa).

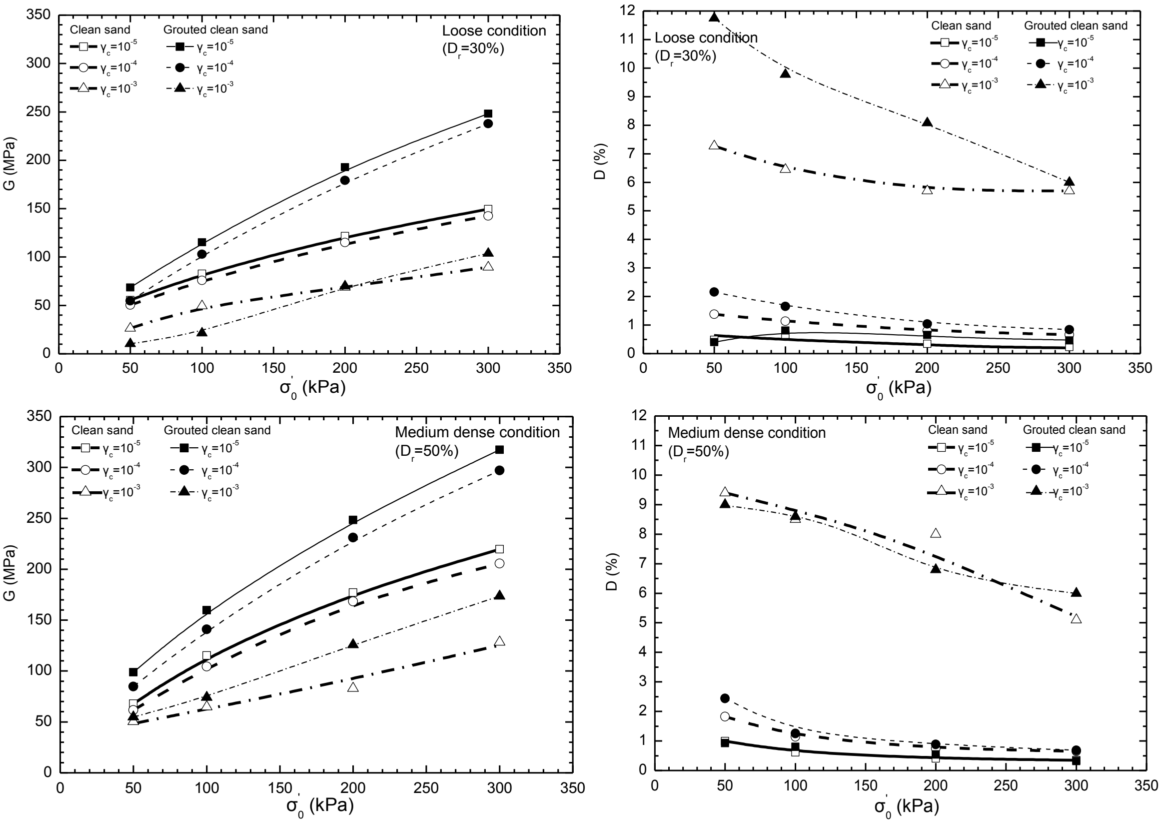

Figure 5. Behavior of non-grouted vs. grouted clean sand

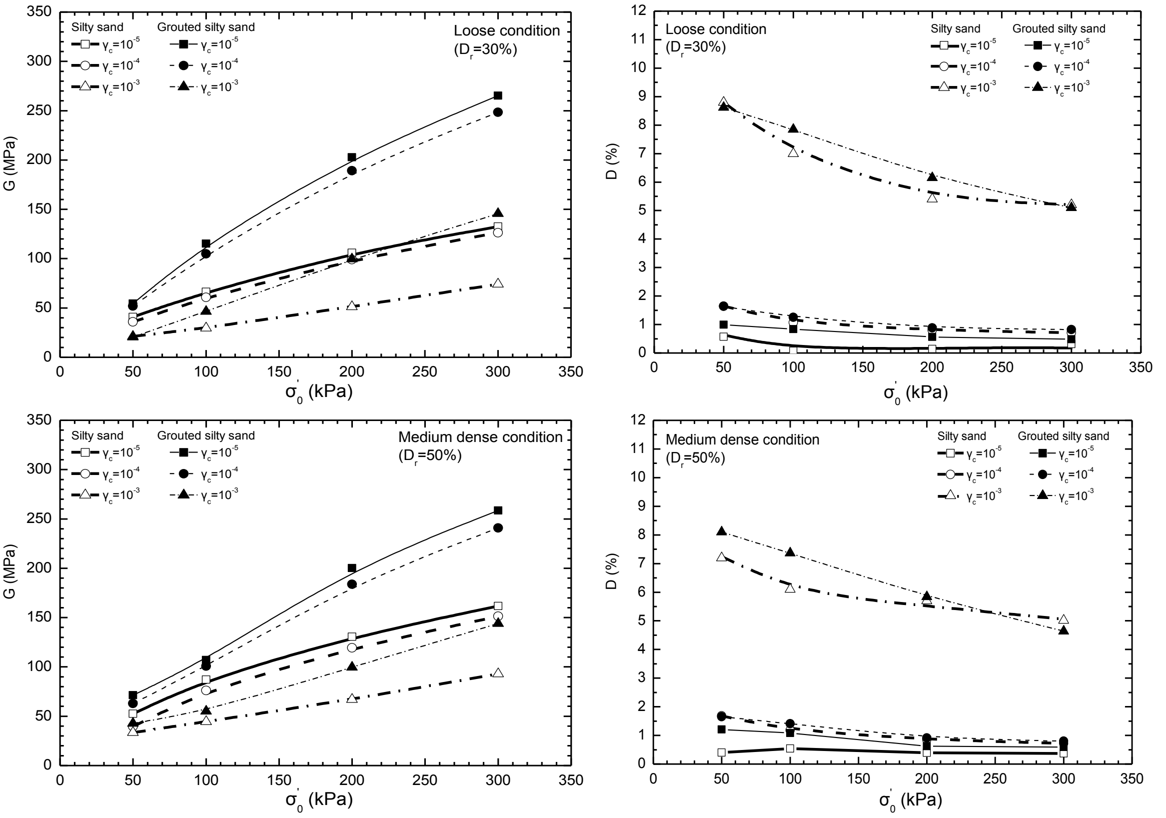

Figure 6. Behavior of non-grouted vs. grouted silty sand

Of particular interest is the comparison of behavior of stabilized clean sand to the behavior of stabilized silty sand, Figure 7 and Figure 8. It is observed that the efficiency of impregnation –in terms of shear modulus increase- depends strongly on relative density: for medium dense conditions, the clean sand is characterized by a more favorable behavior, whereas the effect is reversed for silty sand. Regarding the values of damping ratio, the same trend may be observed: the impregnation is more efficient in the case of clean sand (especially for medium and large shear strains).

The combined effect of shear strain and relative density on the dynamic properties of silty sand is clearly demonstrated in the diagrams of Figure 7. According to this diagram the efficiency of impregnation -in terms of modulus increase- for medium dense condition and medium to high shear strains is of the order of 20%; however the efficiency drops to 10% in the case of loose sand. In terms of damping ratio increase, the efficiency of impregnation is higher for the loose material, being equal to 20%-35%, for shear strains ≈$3*10^{-4}$.

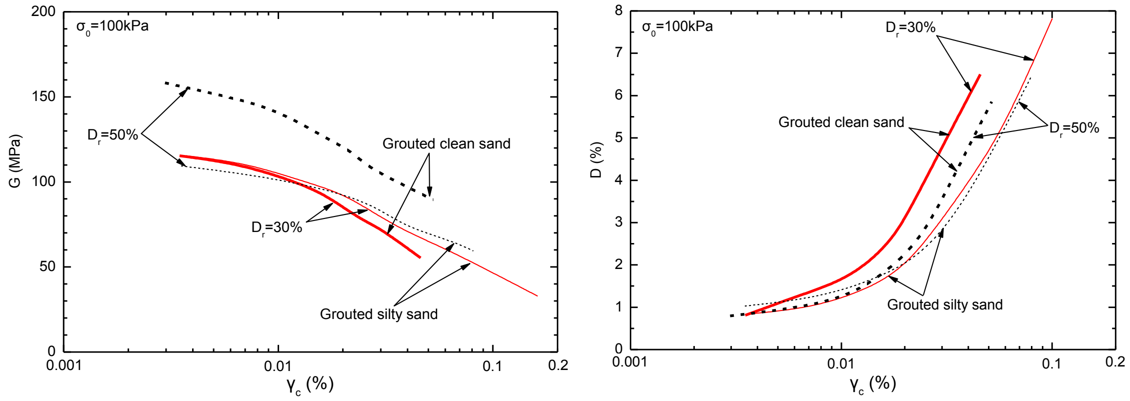

Figure 7. Behavior of grouted clean sand vs. grouted silty sand

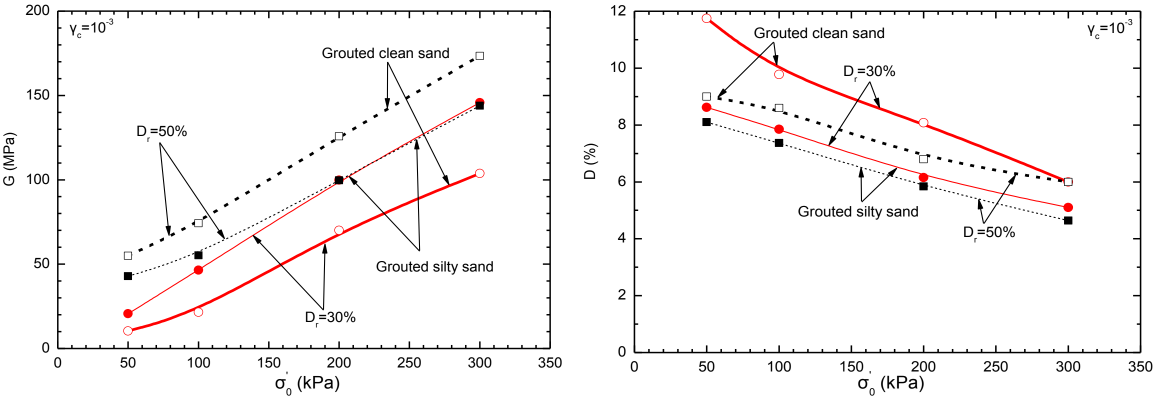

Figure 8. Dependence of dynamic shear modulus, G, and damping ratio, D, of grouted specimens on soil type and relative density and on confining pressure

3.3 Effect of concentration (CS) of solution

The effect of concentration of the injected solution is of paramount importance as it affects the cost of the particular soil stabilization method. In the present study the effect of solution concentration was investigated by performing resonant column tests on specimens impregnated with a CS=6% (L6) solution, and comparing the results with those obtained for CS=10% (L10) and discussed in the previous sections. The diagrams shown in Figure 9 facilitate the above comparison for the case of medium dense condition (D_r=50%). The diagrams indicate a reduction of shear modulus when the concentration is reduced from 10% to 6%. Also, the reduction is negligible for low values of confining stress (in agreement with Spencer et al., 2008, who found that for σ_0=50kPa the effect of colloidal silica grouting is negligible) and reaches the value of 24% for σ_0=300kPa. On the other hand, the reduction of concentration of the silica solution results in an increase of damping ratio ranging from 15% to 50%, for high values of shear strains.

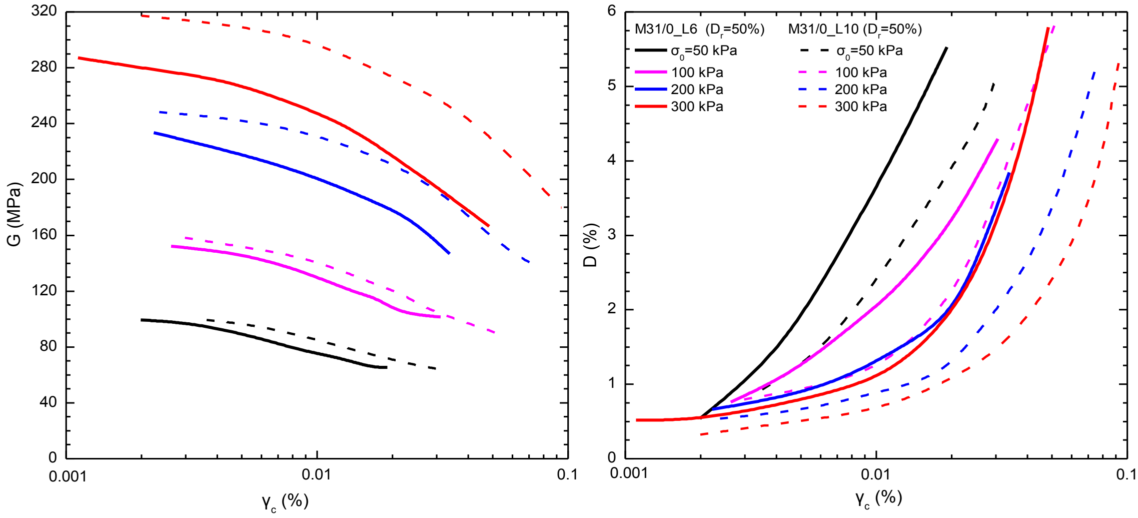

Figure 9. Effects of colloidal silica concentration in grouted clean sand on G-γ_c and D-γ_c relations

4. CONCLUSIONS

On the basis of the test results presented in the previous sections it may be concluded that the damping ratio of soil (clean sand and silty sand) is increased significantly following impregnation, accompanied by an increase of stiffness. The above effects, combined with the fact that no pore water pressure can be generated in the grouted soil, indicate that the passive soil stabilization method studied in the present paper (soil grouting using silica colloids), can be an effective means for mitigating the liquefaction hazard. In particular the following conclusions can be drawn from the experimental program:

1. The impregnation of clean and silty sands with a solution of colloidal silica (CS=10%) results in an increase of both the dynamic shear modulus (G) and of the damping ratio (D) of the treated soil. The efficiency of impregnation is greater in the case of loose soil conditions ($D_r \approx 30\%$).
2. In terms of modulus increase, the efficiency for clean sands ranges from 20% to 65%, whereas for silty sands the efficiency ranges from negligible to 55%. In terms of damping ratio increase, the efficiency ranges from 0% to 55% for clean sands and from 0% to 25% for silty sands.
3. For the case of treated sands, an increase in relative density results in a significant increase of shear modulus, whereas an increase of damping ratio can be achieved only by decreasing the relative density.
4. For impregnated silty sands, the effects described in the (3) above are diminished, i.e. an increase of relative density results in a limited increase of shear modulus and a decreased relative density results in a small increase of damping ratio.
5. A reduction of silica solution concentration (from 10% to 6%) resulted in (a) a reduction of efficiency -in terms of shear modulus increase- up to 20%, for high values of confining stress (σ_0=300kPa), and (b) a significant increase in efficiency -in terms of damping ratio- up to 50%.

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