

LOW PRESSURE GROUTING WITH NANOSILICATES TO REDUCE THE LIQUEFACTION SUSCEPTIBILITY OF SAND

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ABSTRACT

The paper reports an experimental laboratory study aimed at investigating the effectiveness of low pressure grouting with nano-silica compounds as a remedial against liquefaction of sandy soils and to optimize the technique rendering it more attractive from the technical and economical viewpoint.

The grout herein adopted is a three-component mix of an aqueous suspension of sub-micrometric silica particles, water and an aqueous solution of sodium chloride. The latter, raising the pH of the suspension triggers the formation of the silica gel that clogging the soil pores reduces the mobility of the grains and, hopefully, produces a stiffer response and a reduced contractive tendency of the material.

A preliminary set of laboratory vane tests is performed to observe the gelling time of the material and fix the curing time of the samples by measuring the increase of shear resistance.

Thus, reconstituted samples of a silica sand, manufactured at two different initial levels of density are treated with nano-silica grout prepared with a silica concentration ranging from 1.2% to 5.0% in weight. The samples are transferred into a fully servo-controlled triaxial cell and subjected to monotonic drained and cyclic undrained tests at variable stress amplitudes.

The comparison among the monotonic tests on treated and untreated samples reveals an increase of peak strength and a more dilative tendency, increasing with the amount of injected silica. The comparison of cyclic undrained tests shows a lower tendency of the treated material to accumulate excess pore pressures with cycles and a retarded liquefaction proving that the grouting of sands with nano-silica can be profitably adopted to mitigate the effects of liquefaction of loose sandy deposits.

Keywords: sand, liquefaction susceptibility, ground improvement, low-pressure grouting, nanosilicate.

1 INTRODUCTION

Several worldwide examples (e.g. Niigata, 1964 - Anchorage, 1964 - San Francisco, - Kocaeli, 1999 - Christchurch, 2011 - Emilia Romagna, 2012) have demonstrated how seismic liquefaction of sands may affect natural lowland deposits or reclaimed lands and cause remarkable financial losses over large territories. Although the casualties directly connected with liquefaction are rarely of concern, the impact on human establishments, cities, industrial districts, lifelines networks may cripple communities and impair their capacity to recover for long time. The liquefied foundations lose their ability to sustain buildings and infrastructures, the ground flows down in case of even gentle slopes and these phenomena are often accompanied by eruption of sand boils at the ground surface. Normally uneven immediate and post-earthquake settlements of the ground surface occur and, in the most severe cases, lateral spreading turns into the damage of buildings and infrastructures, roads, pipelines underground installations. The

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phenomenon affects saturated loose sandy soils because of their tendency to compress when cyclically loaded by earthquake waves associated to the pore water pressure build-up opposing to this tendency. When the seismic loading is large enough and drainage of water prevented by the boundary conditions (e.g. confining strata of finer material), the excess pore pressure may grow to an extent where it equals the overburden stresses. In this situation, the normal stresses at the contacts between soil grains, quantified by the effective stress in the continuum approach, become nil and the soil loses its capability to resist against shear forces. If structures are present above, inhomogeneous deformation occurs at the foundation level that may turn into intolerable settlements. In the most severe cases, the soil assumes the consistency of a liquid (hence 'liquefaction').

The above effects may be reduced adopting reinforcement or ground improvement techniques. Lattice walls or stiffer isolated inclusions like piles, jet grouting, deep soil mixing or stone columns (D'Appolonia, 1953; D'Appolonia and Miller, 1954), may serve to bypass the liquefiable layers and adsorb the seismic actions, reducing in this way the coupled volumetric-shear deformation of the soil. An alternative countermeasure consists in the massive improvement of soil. Compaction by means of dynamic (Mayne, 1984; Kumar, 2001), vibratory (Kirsch and Kirsch, 2016) or blasting methods (Lyman, 1942; Prugh, 1963) can be applied to increase density of the soil and reduce its compressive tendency upon cyclic loading. A further approach consists in adding binders to the soil with the double aim of providing a cohesive shear resistance at the grain contacts, i.e. not dependent on normal stress, and reduce the mobility of grains that triggers the phenomenon. When selecting the most appropriate treatment, it must be considered that many of the above listed categories are not suitable for existing structures and that less invasive solutions must be sought. Low pressure grouting with clay suspensions, cement or chemical products (Karol, 1968; Donovan *et al.*, 1984) offers an appealing alternative, as injection may be carried out with minimal disturbance for the upper structure. A key issue of these techniques stands in the selection of the grout, that should be made simultaneously considering:

- feasibility of treatments or soil "groutability"
- mechanical effectiveness, i.e. reduced liquefaction susceptibility
- competitiveness, i.e. technical-economical convenience.

The silicate products consist of water suspension of nano-particles (2nm to 100nm size). Due to their very low viscosity, comparable to that of water, this material can be easily injected even in relatively low permeability soils (e.g. fine sands), seep through soil pores and cover large distances. A salty solution is normally mixed with the nanosilicate before the injection to activate a reaction that ends with the production of a gel, filling the soil pores. The speed of this reaction can be tuned controlling the relative amount of the activator. In the present paper, the efficacy of this technique is experimentally investigated pointing out the above aspects with a series of mechanical and chemical laboratory tests. An experimental campaign consisting of undrained cyclic triaxial tests with different cyclic stress amplitude has been initially performed to quantify the liquefaction susceptibility of a reference sand at various levels of density. The same experiments have been then repeated after injecting the soil with nanosilicate suspensions of various composition, i.e. different proportions of nanosilicate, sodium chlorite reactant and water. Scanning electron microscopic observations and X ray diffractions have been performed on the various materials to explore the basic principle of this technique.

2 THE STUDIED MATERIAL

- Sand

The tested sand (named S3) comes from a quarry site (Fossanova in Southern Italy) where it is industrially extracted for glass production. This sand, widely used in the laboratory of University of Cassino and Southern Lazio as a reference material for testing (e.g. Salvatore *et al.*, 2017), is formed by sub-rounded grains, as shown by the scanning electron microscope (SEM) of Figure 1. The grain size distribution is obtained by extracting from the original material, the particles passing the sieve #40 (0.425mm) and retained by the sieve #80 (0.180mm) of the ASTM D422 series. A summary of physical characteristics, including the minimum and maximum void ratio measured by Iolli *et al.* (2015), is reported in Table 1.

Table 1 Physical properties of the Fossanova sand S3.

G_s	D_{50} (mm)	C_u	e_{min}	e_{max}
2.65	0.303	1.6	0.476	0.821

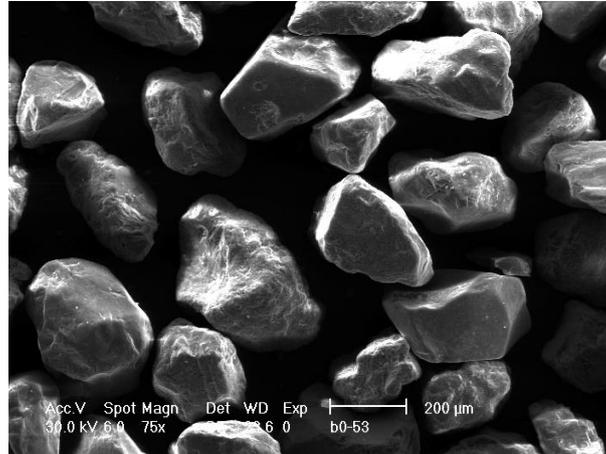


Figure 1 Scanning electron microscope image and main physical properties of the of Fossanova sand S3.

The chemical composition of the Fossanova sand, reported by the producer (Table 2) and substantially confirmed by x-ray diffraction test (XRD) performed in this study (Figure 2), reveals a predominant presence of quartz and irrelevant inclusions of metals. The diffraction planes detected with the XRD test correspond to silicone oxide (the most frequent) and minor compounds like muscovite $KAl_3Si_3O_{10}(OH)_2$ and microcline $KAlSi_3O_8$.

Table 2 Chemical composition of the Fossanova sand S3.

Compound	Concentration by volume (%)
Silicon oxide (SiO_2)	90.00-96.00
Alumina (Al_2O_3)	1.35 min
Iron oxide (Fe_2O_3)	0.13 max
Potassium oxide (K_2O)	1.10 max

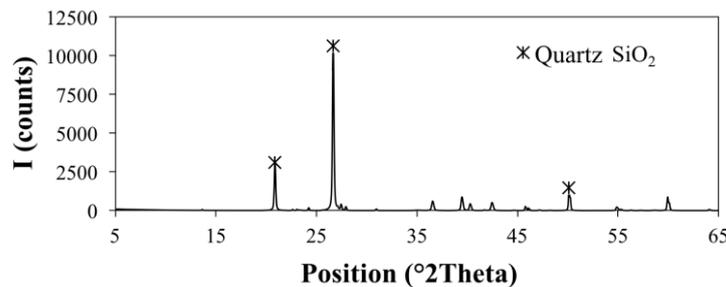


Figure 2 XRD chart of Fossanova sand S3.

The soil samples analysed in the present study have been prepared at two different relative densities, equal to approximately 10% and 60% to quantify the efficiency of the proposed methodology in a wider set of conditions.

- *Nanosilicate grout*

The product used in the present study is an aqueous colloidal-silica suspension with diameter of particles approximatively ranging from 2nm to 100nm and a silica content of 15% in weight, marketed by BASF Chemicals as MasterRoc-MP325. Normally, the suspension has a stable aqueous consistency and possesses a low viscosity (10mPa s). When mixed with an activator consisting of a 10% aqueous solution of sodium chloride, the rise of pH destabilizes the colloidal suspension and triggers the formation of a

gel made of long chains of highly hydrophilic spherical colloids in a state of gel that remains stable in time (Yonekura, 1996). Modifying the proportion between silica suspension and sodium chlorite solution it is possible to vary the gelling time from few minutes to several hours (see Figure 3).

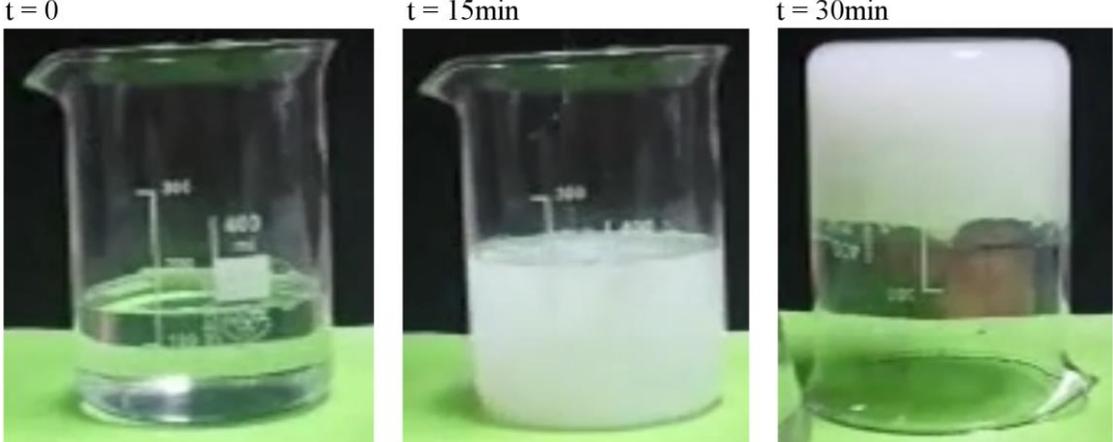


Figure 3 Typical setting process of the nano-silicate grout.

Grouting with nano-silicate products is frequently used as a fast remediation against piping of underground excavations (e.g. Manassero and Di Salvo, 2012; Traldi and Levanto, 2016) or for the sealing of contaminants confining barriers (e.g. Persoff *et al.*, 1994; Moridis *et al.*, 1995). Past studies have also demonstrated the effectiveness of nano-silica grout to reduce the liquefaction potential of sandy soils (Gallagher, 2000; Gallagher *et al.*, 2002; Liao *et al.*, 2003). However, while in these experiments grout mixtures with 5% or more of colloidal silica content by weight were used, in the present work lower concentrations are investigated to consider the unavoidable dilution that occurs when grouting is performed in saturated sands and to optimize the technique and render it more appealing from a technical-economical viewpoint.

Initially, attention has been given to the gelling reaction, and particularly to the time necessary for the grout to acquire the solid consistency, considering this aspect fundamental for the *in-situ* application. To this aim, product and accelerator have been mixed together with different proportions in a small cylindrical container and left at the laboratory environmental conditions (T=20°C). The variation of the gelling time, defined as the time necessary for the grout to remain in the container when this last is overturned, is plotted versus the concentration of activator in Figure 4.

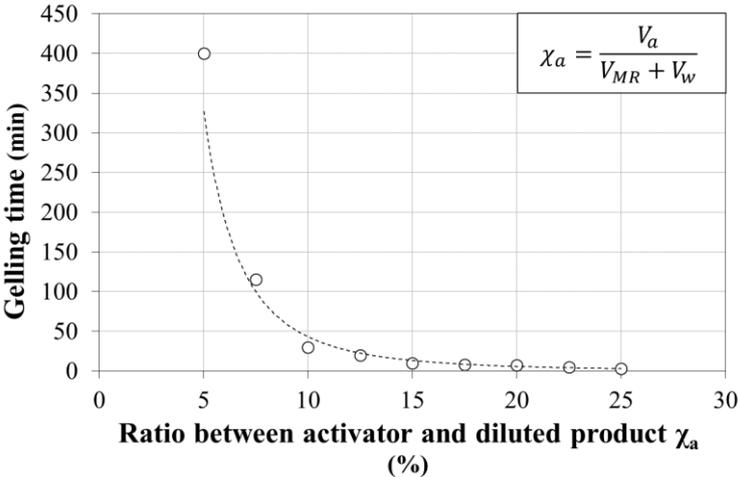


Figure 4 Gelling time versus volume concentration of the activator.

The figure highlights the noticeable relevance of the quantity of mixed activator on the gelling speed, showing that large amount (say more than 10%) produce gelling within half hour or less. On the other side, it must be considered that a too fast setting of the mix inhibits the seepage necessary to propagate the grout in the soil. The above opposite needs must be carefully considered when fixing the proportions among the components of the grout.

Small pieces of silica-gel, known as xerogel, are then subjected to XRD and SEM scanning. The XRD results (Figure 5) show the presence of the gel amorphous phase with a wide band of diffraction planes around 22° and some peaks corresponding to the catalyst NaCl (Halite). The darker amorphous phase of the gel and the lighter crystals of Halite can be noticed in the SEM analysis reported in Figure 5.

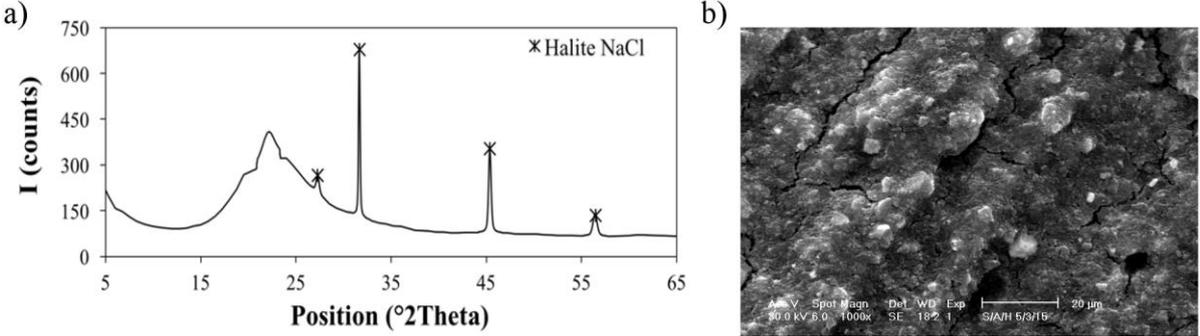


Figure 5. XRD chart (a) and SEM image of the nano-silica xerogel (b).

- Grouted soil

Several samples of sands have been formed and subsequently subjected to low-pressure diffusion of the nanosilicate grout. The injection has been accomplished by producing a low hydraulic gradient seepage from the bottom to the top of the samples (Figure 6.a), trying to guarantee the maximum homogeneity and saturation of the samples with the product. The microstructure of the treated material can be observed in Figure 6.b. The pre-existing skeleton of sand particles is immersed in a matrix of gel. Each grain is coated by a patina that adheres on the surface of the particle, bridges the contacts and fills the interparticle pores. It is thus expected that this microstructure may offer a better resistance against the earthquake shaking and a lower tendency to develop liquefaction, as the mobility of grains and the contractive tendency of the material should be reduced by the presence of the gel.

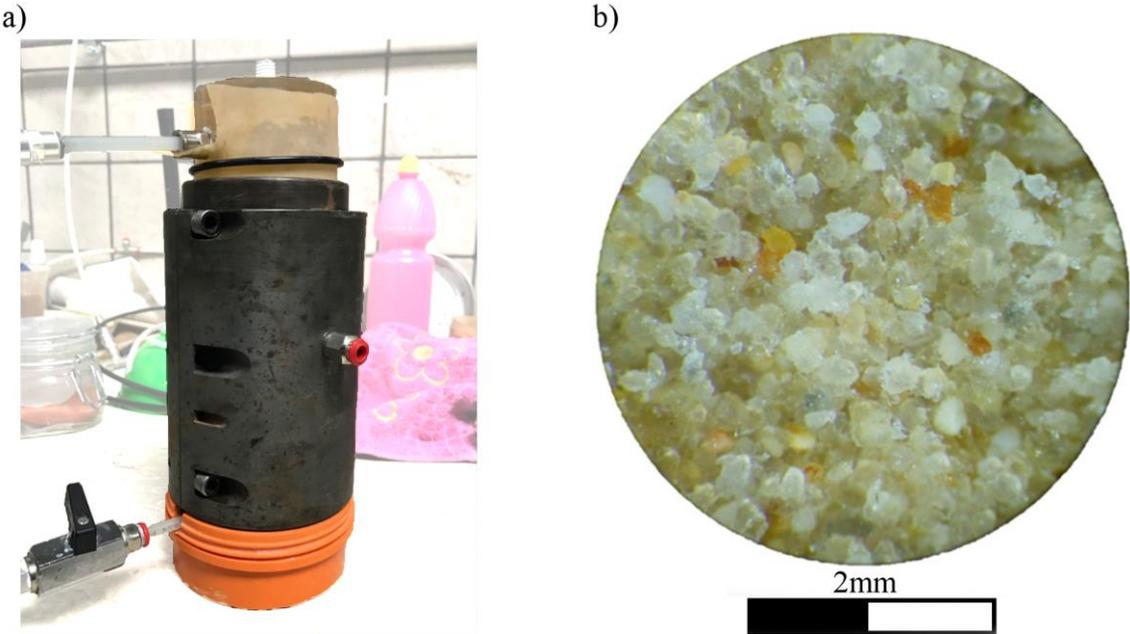


Figure 6. Experimental set-up for the grouting (a) and microscope picture of the treated sand (b).

Since in the field grouting is normally performed in a wet environment and the amount of released product needs to be optimized for economic reasons, the effects of dilution with water have been carefully investigated in the present study. To this aim SEM scans have been taken on sand injected with silica grout formed with different proportions of respectively product with 15% of silica content (product), 10% sodium chlorite solution (activator) and dilution water (Figure 7). In all cases, the material has been oven dried prior to the scanning placing it at 50°C until the mass become stable. The

desiccation, necessary for the SEM technique, produces a volume contraction and exfoliation of the nanosilicate gel, and thus the reported pictures are not fully representative of the real conditions. However, it is seen that the gel adheres on the surface of the sand particles bridging the mutual contacts and filling the interparticle pores. The presence of gel is very pervasive for the case where product and activator are only injected (a), there are relatively small clusters and filaments of nano-silicate for 16.6% of injected product (case b), while the presence of gel clusters almost disappears when dilution reaches higher degrees (case C).

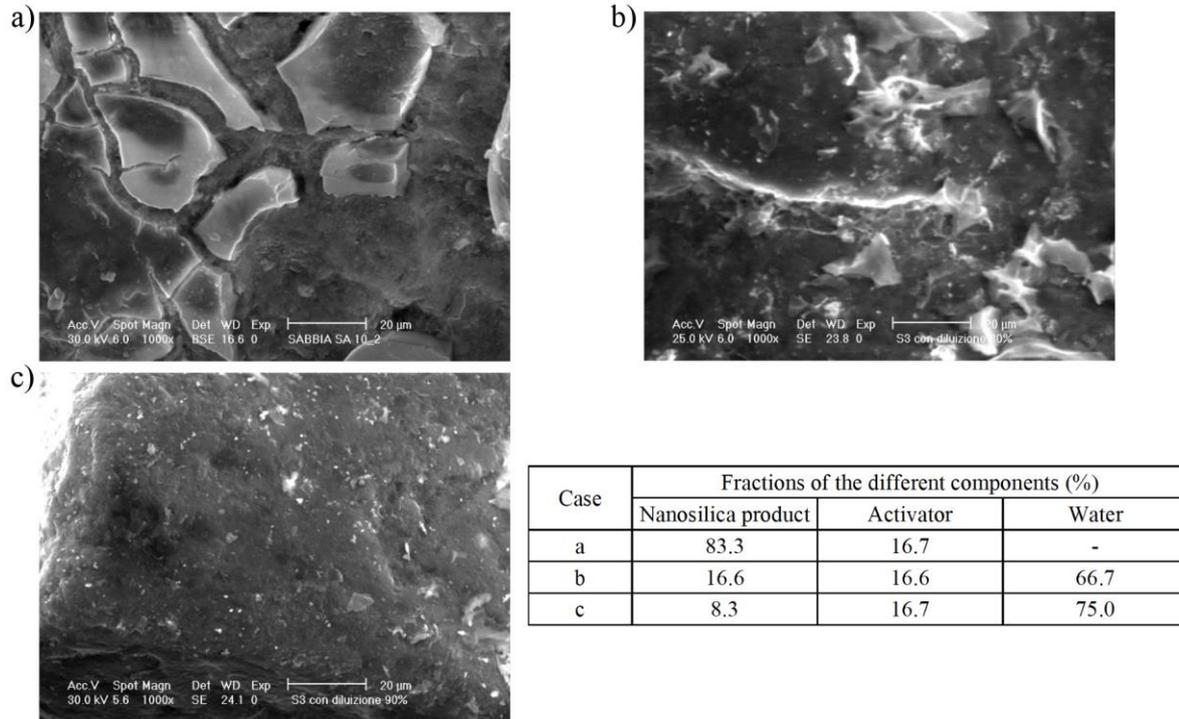


Figure 7. SEM images of the grouted sand for different dilution of the nanosilica gel.

To monitor the development of the reaction and fix the curing time of the samples subjected to the mechanical tests, laboratory vane shear tests have been carried out at different time intervals on the injected samples. With this aim, several samples have been formed by pluviation to give an initial void ratio of about 0.8 and then then treated with grouting suspensions prepared with the proportions among the ingredients reported in Table 3. The proportions have been established to give three different concentration of solid silica (w_s in Table 3 represents the concentration by weight of solid nanosilica over the total amount of injected grout).

Table 3 Composition of the grout mixes in the experiments of Figure 8.

ID	MasterRoc MP325 (%)	Water (%)	Accelerator (%)	w_s (%)
1	25.00	58.30	16.70	3.75
2	16.70	66.60	16.70	2.51
3	8.30	75.00	16.70	1.25

The vane test (ASTM 4648 2000) on each series of samples has been performed at different curing time (from 3 hours to 28 days) adopting a specifically conceived rail guide system to ensure the verticality of the tool during its insertion and rotation (Figure 8.a). The vane shear resistance (Figure 8.b) shows a fast increase with time that ends with a plateau at 28 days. Almost the 80% of the ultimate resistance is gained after about 5 days, and so this curing time has been chosen for the samples subjected to the mechanical tests. Similar results are reported by Yonekura and Miwa (1993) and Persoff *et al.* (1999). It is worth noting that the shear resistance depends significantly on the amount of injected silica (w_s), being the last measured values about 240, 530 and 680 kPa (for respectively w_s equal to 1.25, 2.5 and 3.75%) versus an initial value (for the untreated sand) of 30 kPa.

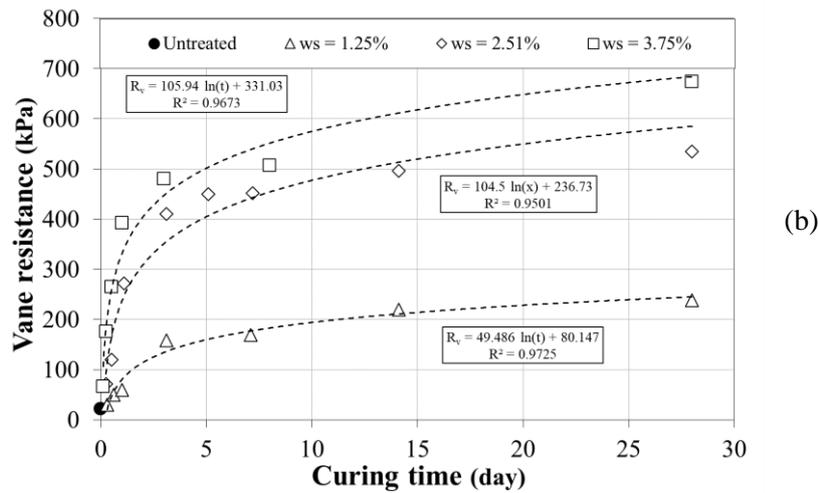
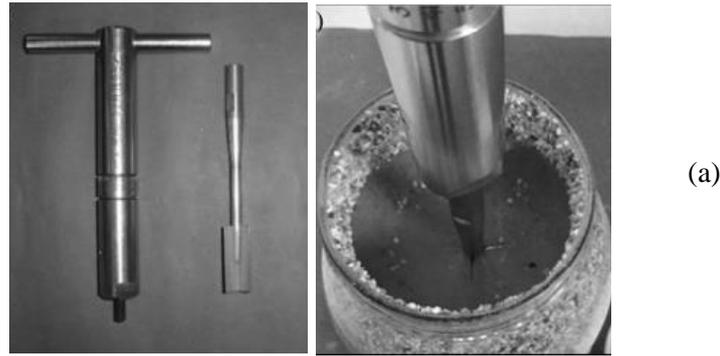


Figure 8 Laboratory vane test on the grouted samples (a. equipment; b. time increase of the vane shear resistance).

3 TRIAXIAL TESTS

The mechanical response of the treated sand has been investigated performing monotonic consolidated-drained and cyclic undrained triaxial tests on cylindrical samples of 70 mm diameter and 140 mm height, prepared at a specified relative density. The samples were formed by pluviating the sand in thirteen layers of 1 cm thickness each and applying on the top of each layer one single blow of tamping with a 1 kg weight falling from a height of 40cm. This procedure enabled a reasonable repeatability, providing samples with initial void ratios contained within the range $e_0 \approx 0.61-0.62$ (corresponding to a relative density $D_r \approx 60\%$). The soil was then subjected to a low gradient seepage with nanosilicate compounds, adopting different proportions among the ingredients, with the equipment reported in Figure 6.a. After curing (normally, five days were assigned as standard time), the sample was moved in the testing apparatus, a servo-controlled Bishop and Wesley triaxial cell, placing care in its saturation. With this aim, carbon dioxide was initially flushed from the bottom to the top for thirty minutes and the pore pressure was raised to values equal to 600 kPa to adsorb possible gas bubbles.

- Consolidated-drained monotonic tests

The results of three consolidated-drained monotonic tests performed at an effective confining stress of 200 kPa on natural sand and on soil with different concentration of solid nanosilicate w_s (1.7 and 5%) reported in Figure 9.a. It shows the effects of grouting and, more particularly, of the proportion of solid nanosilicate concentration on the stress-strain response of the material. The most evident modification of the material behaviour consists in an increase of the shear strength at peak, with a gain of 16 to 30% of the maximum deviator stress for w_s equal to respectively 1.7 and 5%. A more detailed analysis of the curves and particularly of the volumetric behaviour reveals that the response of the grouted material

becomes progressively more brittle. In fact, apart from the initial part of the stress-strain curves, affected by some accommodation between end platens and sample bases, the response of the original soil shows the typical decay of stiffness, accompanied by a continuous dilation that reaches its maximum rate at peak and decays with softening. Comparatively, the treated material has a delayed dilative tendency, as a larger contraction seems to prevail in the initial phase. However, the dilation rate at peak reaches progressively larger values with the amount of solid nanosilicate, the post-peak softening becomes faster and more marked, the tendency to dilation suddenly stops in the last part of the test. These differences can be more clearly understood when looking at the shape of the samples after the tests (Figure 9.c). In fact, while the natural soil shows the barrel shape typical of a relatively homogeneous deformation throughout the sample, a tendency to localize deformation around shear bands occurs in the treated samples, being more evident for the higher nanosilicate content.

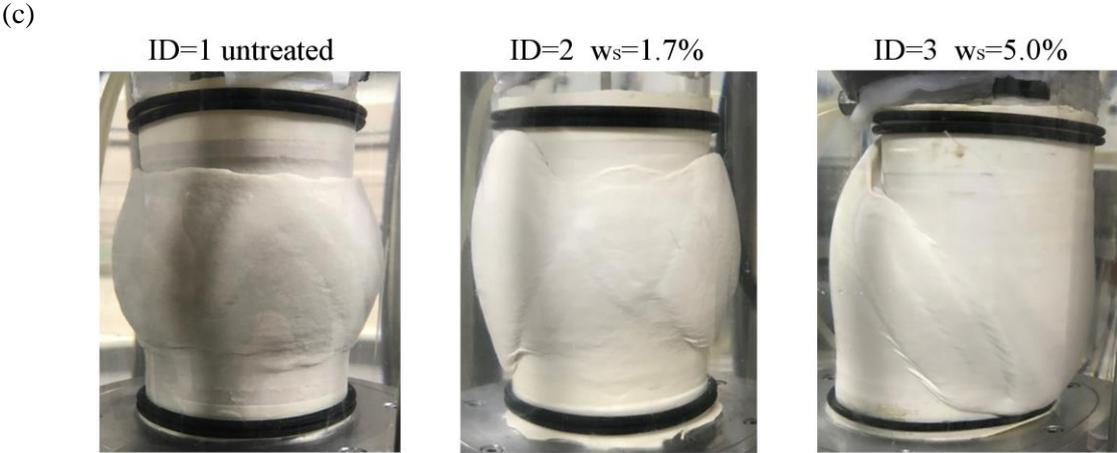
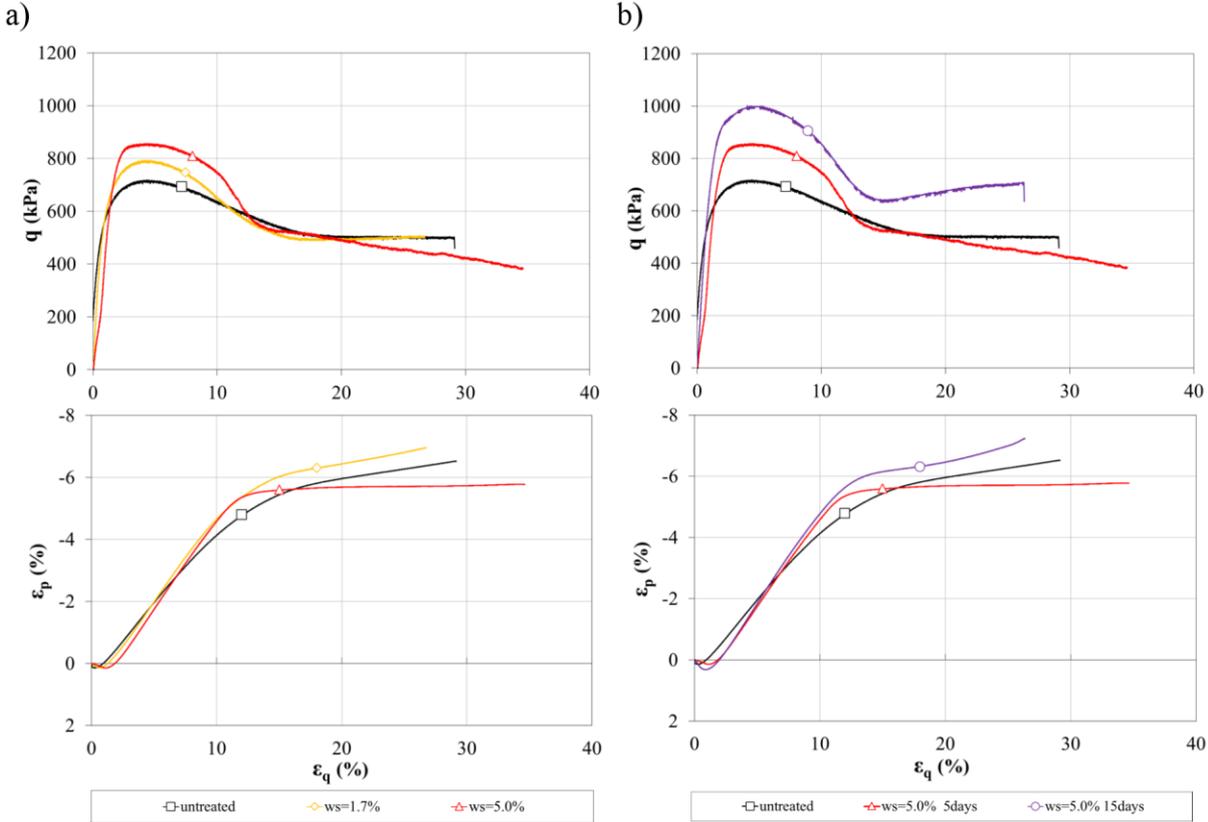


Figure 9 Monotonic triaxial tests on natural and grouted samples carried out with 200 kPa effective confining stress (a. tests on the various materials after 5 days curing; b. tests on sand grouted with 5% concentration of solid nanosilicate at different curing time; c pictures of the samples of figure a taken after the tests).

It is finally worth observing that the above trends increase with time (see Figure 9.b) as a confirmation that the fixed curing time, mostly coming from experimental needs, is just an inductive reference and that the improvement of soil response achieved with the nanosilicate grouting can be larger than seen in the present experimentation.

- *Cyclic undrained triaxial tests*

The effectiveness of nanosilica grouting to reduce the liquefaction susceptibility of the sandy soil is demonstrated by a series of cyclic triaxial undrained tests performed on samples of original and treated soil. The tests were performed on samples prepared at initial void ratios ranging between 0.61 and 0.65, applying an initial effective confining stress of 100 kPa. Variable cyclic stress ratios (CSR defined in Equation 1) were applied observing the development of excess pore pressure and computing the number of cycles that triggered liquefaction (n_{liq}). This condition has been defined as the state where the pore water pressure ratio r_u (defined in Equation 2) is equal to 0.9.

$$CSR = \frac{q}{2 \sigma'_{v0}} \quad (1)$$

$$r_u = \frac{\Delta u}{\sigma'_{v0}} \quad (2)$$

An example of test results is shown in Figure 10 for the natural (10.a) and treated (10.b) sand. In both cases there is a progressive tendency to accumulate pore pressure and reduce the mean effective stress. A detailed insight at the p' - q curves reveals that the natural soil has a continuous tendency to contract, that starts with the first loading and proceeds with a relative rapidity for the subsequent large unloading-reloading cycles. Comparatively, the treated soil shows a tendency to dilate, and thus to develop negative excess pore pressures, during the first loading. There is an accumulation of excess pore pressure during the subsequent cycles, but it proceeds with a much slower rate. The condition $r_u=0.9$ is achieved after 15 cycles for the natural sand, after 58 cycles for the treated sand.

The results of these and other tests are then collected in Figure 11 where the number of cycles producing liquefaction are plotted versus the applied CSR. The largely different resistance to liquefaction offered by the natural and treated soil is immediately shown. In details, the cyclic stress ratio not causing liquefaction is about 0.15 for the natural soil, about 0.25 for the treated soil, with an increase of 67%; the number of cycles that causes liquefaction varies generally from three to four times between natural and treated soil. In general, the susceptibility of soil to liquefaction is strongly reduce by the low-pressure grouting. A weaker effect has been seen so far for lower concentrations of solid nanosilica, but the experimental campaign needs to be completed.

4 CONCLUSIONS AND FUTURE DEVELOPMENTS

The presented study aims to investigate by means of an experimental campaign the effectiveness of low pressure grouting with nanosilica products to reduce the liquefaction susceptibility of a sand. The tests performed on a uniform silica sand, have demonstrated the effectiveness of the proposed solution and the importance of calibrating the composition of the grout. Basically, the nanosilica product can be injected through the soil by low-pressure grouting thanks to its low viscosity. With the reaction, a gel is formed that coats the soil particles and fills the intergranular pores. The preliminary study on the formation of the gel has proven the flexibility of the technique showing that the speed of the reaction can be controlled, varying the gelling time from few minutes to several hours by dosing the amount of accelerator. The mechanical tests have shown that the use of the products can be optimized by searching the maximum level of dilution necessary to achieve the mechanical performance.

The vane tests performed at various time intervals on soil treated with different grout has shown that the mechanical strength increases with time, reaching higher values for larger fractions of injected solid silica. The drained triaxial compression tests have shown an increase of the peak strength and a more dilative and brittle response of the treated compared with the original material, these effects being more pronounced for higher contents of solid silica.

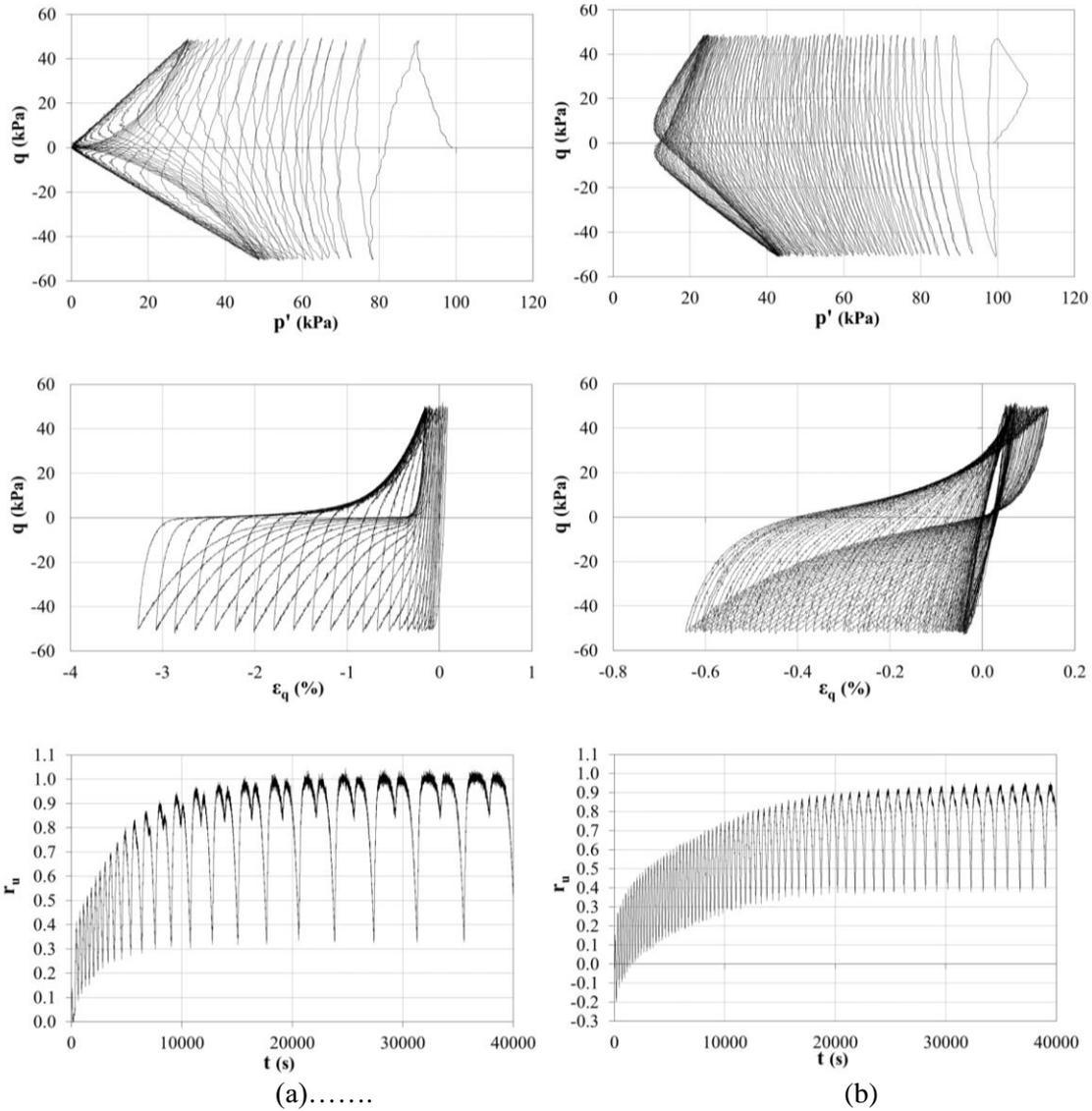


Figure 10 Cyclic undrained triaxial tests on natural (a) and grouted ($w_s=5\%$) sand (b) carried out with 100 kPa initial effective confining stress ($CSR=0.25$, $e_o=0.62$).

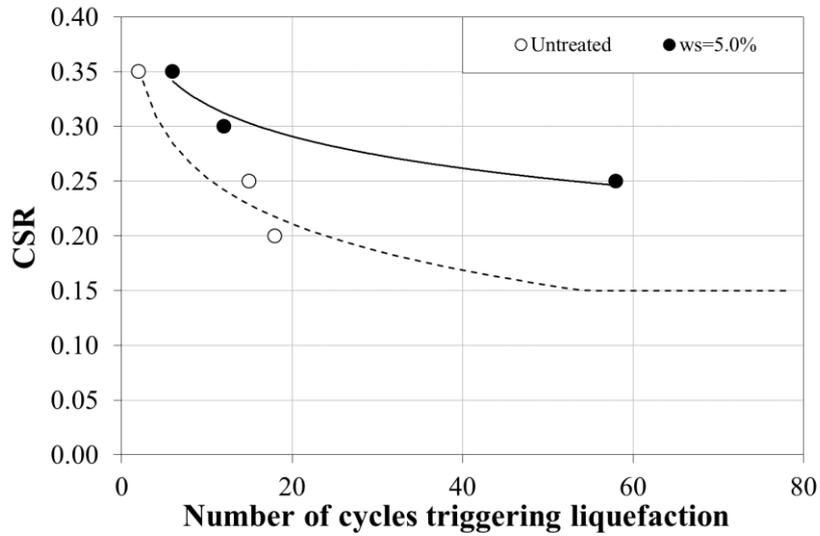


Figure 11 Cyclic undrained resistance on natural and grouted ($w_s=5\%$) sand (b) carried out with 100 kPa initial effective confining stress ($e_o=0.61-0.65$).

Finally, the undrained cyclic triaxial tests have revealed that the silica-gel reduces the tendency of the material to develop excess pore pressure and thus to increase the liquefaction resistance of the sand. All the above effects have been seen on a relatively dense material ($D_r=60\%$), and are believed to be more relevant on very loose soil, not yet tested in the present investigation.

5 ACKNOWLEDGMENTS

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