Porcino D, Ghionna V., Granata R., & Marcianò V. (2016). Laboratory determination of mechanical and hydraulic properties of chemically grouted sands. *GEOMECHANICS AND GEOENGINEERING*, vol. 11 (2), p. 164-175, ISSN: 1748-6025, doi: 10.1080/17486025.2015.1057621

Geomechanics and Geoengineering: an International Journal

ARTICLE TYPE : REVIEW ARTICLE

Article Title: **LABORATOIRY DETERMINATION OF MECHANICAL AND HYDRAULIC PROPERTIES OF CHEMICALLY GROUTED SANDS**

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Abstract

The purpose of this paper is to investigate mechanical and hydraulic properties of sands treated with mineral-based grouts through the results of a laboratory test program consisting of unconfined compression tests (UCS), triaxial bender element tests (BeT) and constant flow permeability tests in triaxial apparatus. An improved apparatus was set up for obtaining high quality" multiple grouted specimens from a single column. Two selected natural sands having different grain sizes were grouted with two mineral-based silica grouts, resulting in different levels of improvement. The behaviour of the sands treated by mineral grouts, in terms of strength, initial stiffness and permeability, was compared with that exhibited by a more traditional silicate grouts. The results of this study indicate that sands treated with mineral grouts result in higher strengths, higher initial shear modulus and lower permeability values than the sands treated with the silicate solution. The effect of grout type, effective confining pressure, and sand particle-size on small-strain shear modulus of grouted sand specimens was evaluated. Based on test results, the small strain shear modulus increment from treated to untreated specimens has been correlated with the unconfined compressive strength, obtaining a unique relationship regardless of grout type and grain-size of tested sands.

Keywords: chemical grout, sands, strength, initial stiffness, hydraulic conductivity

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Introduction

Chemical solutions based on sodium silicate is a well-established geotechnical process (Gouvenot 1998, Karol 2003) for waterproofing and strengthening of the ground with numerous applications in civil engineering. In virtue of their rheological properties, these chemical treatments can be successfully employed even in fine sands or sands containing low silt content. The properties of silicate-grouted sands have been studied by many researchers (Ata and Vipulanandan 1998, Clough et al. 1979, Diefenthal 1979, Kaga and Yonekura 1991, Krizek et al. 1982, Maher et al. 1994, Tsukamoto et al. 2006). The increasing concern about risk of pollution under the water table has limited the use of sodium silicate solutions with organic reactants. On the other hand, silicate based solutions with inorganic reagents can produce only soft gels and, hence, they are better used for water stop problems in sands. This has led to the research and development of a fairly new type of chemical grout, such as mineral silica grouts and, more recently, colloidal silica grouts. These grouts appear attractive as an alternative grouting method for reducing settlements in liquefiable sands or silty sands beneath existing structures (Gallagher et al., 2007; Rodriguez et al., 2008) and for improving dynamic properties of sands (Spencer & Rix, 2008).

Mineral grouts are composed by mixing an activated silica liquor with inorganic reagents based on calcium, permitting uniform treatment of medium to fine sands (Dano et al. 2004, Gouvenot 1998, Tornaghi et al. 988). Unlike colloidal solutions, the liquor is a true silica solution. The activated dissolved silica, associated with the mineral reagent, produces hydro-silicates with a crystalline structure similar to that obtained by hydration and setting of cement; the resulting product is a complex of permanently stable crystals that impart stronger features to the treated soil and high resistance to most of the usual aggressive environments. Furthermore, experimental results gathered from creep tests show much lower long-term deformability at the same stress level and creep rupture at about a two-fold stress level (85% against 45% in silica gel grouts) (Tornaghi et al 1988).

Applications of this method of permeation grouting concern, for example, tunnelling excavations of the Milan underground railway network (Italy) (Tornaghi et al., 1988) and Turin railway interchange (Italy) (Pellegrino, 1999). Recent data published in literature on sands grouted with these new grouts are mainly focused on compressive and tensile strength properties (Dano et al. 2004), creep and fatigue behaviour (Delfosse-Ribay et al. 2007) and dynamic properties of such materials (Delfosse-Ribay et al. 2004). However, a careful review of experimental results relative to chemically grouted sands obtained in literature from various sources often evidence an excessive scattering or a large discrepancy in the results, due to different factors, among them the effect of preparation technique of grouted samples and test procedures. The preparation of the grouted sample should follow a systematic procedure for obtaining homogeneous, repetitive grouted samples. This aspect appears relevant especially for lightly cemented grouted samples, which are extremely sensitive to disturbance effects caused by extrusion, sampling or trimming operations.

Another important item concerns the capability of checking the homogeneity of in situ treatment with lightly cementing grouts; it cannot be pursued through laboratory tests on undisturbed samples. Non invasive tests, such as seismic tests based on in situ measurement of shear wave velocities (V_s), are very attractive. However, to give a practical meaning to this approach, one should be able to link the measured V_s values (or alternatively the corresponding Go values) to the strengthening effect induced by the grouting, or else to the unconfined compressive strength (q_{ucs}) of the treated soils.

This paper presents an experimental comparative study of the mechanical and hydraulic behaviour of two sands grouted with three different grouts, namely a silicate grout, and two mineral based grouts. A detailed description of the improved grouting system specifically designed for obtaining very homogeneous and repetitive "high quality" multiple grouted sand samples is provided.

The results are examined in terms of an "improving factor", defined as the ratio of the shear modulus after grout treatment on its value before treatment, taking into account the influence of effective confining stress, sand grain-size and grout type. Finally, a correlation between the mall strain shear modulus increment from treated to untreated specimens and q_{ucs} values of treated sands is proposed.

Tested materials

In order to investigate the effects of sand grain size on mechanical properties and permeability of grouted sands, two clean and uniform silica sands dug out from different sites along Ticino river (TS) were adopted, namely Ticino coarse-medium sand (termed SM) and Ticino medium-fine sand (termed TSF). These sands were groutable by all grout solutions. Table 1 summarizes the main features of the sands while their grain size-distribution curves are depicted in figure 1.

Three different chemical grouts, capable of imparting a different degree of improvement, were used in the investigation, namely: two mineral silica-grout solutions (defined MG1 and MG2), and a more traditional sodium silicate grout type.

-*Sodium silicate grout*

The solution is composed of sodium-silicate, water and an inorganic reactant. The gelling agent utilized in the present research is a trivalent-metal-salt able to produce a very stable gel. This chemical treatment imparts small cohesion to stabilized soil, locking the ground particles together to provide the desired stabilization. The setting time of the grout was 60-90 min at a temperature of 25-20 °C. The initial viscosity was 2 CP and the density was equal to 1.1 g/cm^3 at 20 °C. This grout is a non-particulate solution which is found to be free from those phenomena of decantation or presso-filtration which could reduce the ability to permeate a soil formation. In virtue of its rheological properties, the solution can even be successfully injected into fine sands or sands containing low silt content.

-*Mineral grouts*

The adopted mineral- based grouts consist of a mix of silica liquor with a calcium-based reactant. Reaction in soil grouted by mineral-based grouts leads to the formation of silicate crystals which are strong and insoluble, resulting in a stronger end product more resistant to most of the usual aggressive environments.

The mineral grout "*MG1*" is Silacsol. At 20 °C, the grout has a density of 1.35 gr/cm^3 and initial viscosity of 12 CP. It maintains a Newtonian behaviour (no cohesion) in the initial phase, then evolve to Binghamian behaviour (with development and increase of cohesion) and sets in about 60-100 min, depending on the environment temperature.

The second mineral grout *"MG2"* is characterized by a lower density (1.25 gr/cm^3) and higher initial viscosity (18 CP at 20 C). The rheological behaviour of MG2 versus time is similar to that of MG1, except for its evolution and setting, which are faster.

Laboratory preparation of grouted sand samples

The mechanical properties of grouted sands especially those treated with low cementation agents are affected by several parameters associated with specimen preparation and testing procedure. They can be listed as follows: curing environment, curing time, specimen size, moulding technique, end conditions, amount of grout flow, distance of the specimen from the point of injection, grout injection pressure, and strain rate of testing (ASTM D4320M-09. Chang et al. 1990, Christopher et al. 1989, Delfoss-Ribaye et al. 2004, 2007, Ismail et al. 2000;; Schwarz and Krizek 1994, Tailliez 1998). In the present research an improved preparation technique capable of providing uniform and repeatable grouted sand specimens was developed. The adopted system consists of a cylindrical plexiglass mould, 70 mm in internal diameter and 600 mm in height, which can be split lengthwise, and was designed for preparing multiple grouted specimens in each grouting phase. This will eliminate the disturbance effects caused by the extrusion of the samples in more traditional systems and , in addition, will avoid further sub-sampling operations for reducing sample length before testing. A picture of the system is shown in Figure 2.

The column was sized to obtain four grouted specimens of 70 mm in diameter and about 140 mm in height. Individual specimens can be easily separated with the filters which were inserted at the interface between the specimens so that no other possible disturbance operation will be required successively. The top and bottom plexiglass caps represent the end boundaries of the samples during grouting.

The preparation procedure adopted in the tests consists of the following phases:

-a known amount of oven-dried sand was placed in four layers: each of them was air-deposited by a funnel from a limited fall height and then compacted to reach a prefixed relative density index (I_r=70%). Compaction of each layer was realised by "tapping" externally on the lateral surface of the mould while maintaining a small seating load on the sample cap. The boundary confinement due to the presence of the cap makes a more uniform sand densification possible, as experienced by the authors in previous research. At the lower and upper ends of the column, a layer of coarse sand was placed as a filter in order to disperse grout in a more uniform manner over the entire area of the specimen.

Homogeneity checks were carried out to ensure that relative density of the densified sand inside the cylinder was sufficiently uniform along the whole length of the column. These checks provided satisfactory results (local deviation less than 0.5 %).

After the pluvial depositional phase, pre-saturation was performed before grout injection to duplicate field conditions of saturated natural deposits under water level. To allow for air-bubbles trapped in the sample to be removed, first CO_2 flow, and then de-aired water under a low gradient were flushed upward through the specimen. The whole process takes about 120 minutes to complete. The injection pressure was selected depending on the rheological properties of the grout and maintained constant during the permeation grouting. Pressures varying from 40 kPa to 170 kPa were adopted. The specimens were left to cure in the mould for a prefixed period (from three to four days); afterwards, the column was dismounted and kept in a moist room at a temperature of 23 °C and a relative humidity of not less than 96%) sealed in a plastic bag. Before testing, the weight, height and diameter of each grouted sample were determined (Figure 3b). Samples stabilized with silicate grout were tested just after retrieval from the column, while those grouted with mineral grouts were allowed to cure for a longer period in the moist room and tested after about 30 days.

Experimental program and procedures

The tests performed on grouted specimens of each column comprise **(figure 3a):** triaxial bender element tests (BeT), unconfined compression tests (UCS), permeability tests in triaxial apparatus (PeT).

Bender element tests

In the present study, bender element tests were conducted on both treated and untreated sand samples for the assessment of the shear wave velocity (V_s) and the maximum shear modulus (G_0=G_{max}) of soil samples, which is a key parameter in small strain dynamic analysis. Tests were performed on fully saturated specimens under different effective confining stresses. The saturation phase was standardised for all tests and this was achieved by applying a back-pressure equal to 300kPa inside the specimen for more than 12 hours. Saturation was continued up to a Skempton B-value = 0.95. The saturated samples were isotropically consolidated up to a cell pressure of 200 kPa and changes in volume of samples during consolidation were assessed through a volumometer. Generally treated samples (particularly those improved by mineral grouts) evidenced low volumetric strains. Small strain stiffness was evaluated from shear wave velocity measurements at a curing time of about 30 days for samples grouted with mineral grouts, and 3 to 4r days for samples stabilized with silicate grout.

A small cavity was made on each end of the specimen and filled with fresh gypsum just before testing; afterwards, the bender elements were pushed into the fresh gypsum to ensure good contact between bender elements and grouted samples (Baig et al. 1997).

Although the bender elements method is a relatively simple technique to obtain values of the small strain shear modulus of soils, the main difficulty is the determination of the travel time of the shear wave. For this reason, the effect of the frequency of the input signal in the considered range of confining stresses, was investigated in order to minimize system noise and provide a clear identification of the first arrival time. Usual frequency range for sands and lightly cemented sands is from 3 to10 kHz, as illustrated in figure 4, while for sand treated with mineral grouts higher frequencies proved to be more effective (i.e. in the range from 10 to18 kHz). Signal interpretation from BeTs was conducted by adopting two different methods, to obtain the “correct” arrival time”, namely the conventional “first arrival” method (Brignoli et al. 1996; Jovicic et al. 1997, Lee &

Santamarina 2005, Mohsin and Airey 2003, Viggiani and Atkinson 1995) and the cross-correlation technique (Lee and Santamarina, 2005; Mohsin and Airey, 2003). The cross-correlation function CC_{xy} has been evaluated by taking the fast Fourier transforms of the input signal X(T) and output signal Y(T). According to Mohsin and Airey (2003), the correct time delay should correspond to one of the peaks of the cross-correlation function. A good agreement between Vs values detected from the two interpretation methods was found as illustrated in Figure 5.

Unconfined compression tests

A triaxial cell was used for determining unconfined compression strength of treated sand samples. All tests were performed in accordance with ASTM D4219-08 at the selected strain rate equal to 1 %/min.

For field applications, it is relevant to know both short term (when the need of strengthening is temporary) and long-term improvement of soil properties. With the aim of investigating the influence of curing time on unconfined compressive strength of the grouted sand samples, a preliminary series of UCS tests were carried out on samples cured in different times, namely 7, 28 and 80 days. Figure 6 presents the unconfined compressive strength as a function of the curing time for sand samples grouted with MG1 and MG2. It is readily apparent that the unconfined compressive strength increases with the increase of curing time. This means that the samples become stronger as they cure and that curing time is an important variable in the response of mineral grout stabilized soils. Regardless of the differences in the final strength, the largest part of the strength gain occurred during the first 28 days. Data reported in figure 5 refer only to specimens treated with mineral grouts; on the other hand results gathered in a previous research (Porcino et al. 2011) on sand samples stabilized by silicate grout, evidenced that the effect of curing time on strength properties is not significant over the considered period of curing time (i.e. 30 days). Grouted specimens should be cured under conditions which prevents moisture loss or volume change of the sample. Preliminary tests were carried out to verify the effect of the lateral confinement during curing time on unconfined compression strength of samples treated with all different types of grouts. The results evidenced that peak unconfined compressive strength of sands treated with silicate grout were significantly affected by the presence of a rigid boundary during curing time resulting stronger and stiffer with respect to samples cured with no lateral confinement. Conversely, the effect of confinement was not significant for samples stabilized with mineral grout.

Permeability tests

To properly evaluate permeability properties of grouted sands, constant flow permeability tests (PeT) were carried out using a flow-pump system (Aiban and Znidarcic 1989, Sembenelli and Angeloni 1992, Zhang et al 1998). The use of the flow pump system is equally appropriate for both low and high permeability soils but the advantages are more apparent when testing less permeable soils, since it allows a considerable saving of testing time. In the flow pump techniques, the hydraulic conductivity (k) of the specimens is evaluated from the steady state response of the head difference (Δh) across the specimen induced by an externally imposed constant flow rate (Q), using the well-known Darcy's law for flow through saturated porous media.

The flow pump system adopted in this study is capable of supplying a constant flow of de-aired water over a e range of $2{\cdot}10^{-10}$ m^3/s to $2{\cdot}10^{-12}$ m^3/s in relation to the hydraulic features of tested samples. Permeability tests were performed on fully saturated grouted specimens, isotropically consolidated up to a prefixed effective consolidation stress (σ'_c=100 kPa). The hydraulic conductivity of the adopted medium and fine Ticino sands reconstituted by pluvial deposition method at the same density index (I_r =70%) of the grouted specimens was $k=5{\cdot}10^{-3}$ m/s and $k=4{\cdot}10^{-4}$ m/s, respectively.

Analysis of results

Unconfined compressive strength

Figure 7 reports the variation of unconfined compressive strength as a function of distance from the bottom of the column for both medium and fine Ticino sands, improved with different grouts. It is evident that grain size affects the unconfined compressive strength of grouted samples, with a general increase in strength, as the grain-size of sand decreases. In fact with the decrease of mean grain-size and, the corresponding increase of their specific surface, a systematic improvement of strength characteristics of grouted specimens can be observed.

The compressive strengths of lightly grouted samples such as silicate grouted sands assume average values ranging from 76 kPa to 124 kPa for medium and fine sands, respectively. Conversely, significantly higher values of peak unconfined compressive strengths were measured on samples stabilized with mineral grouts. For TSF grouted with MG1, q_{UCS} values are equal to 920 kPa on average; for the same sand grouted with MG2, q_{UCS} values can be twice those relative to medium sand. Figure 7 evidences that, although there is some scatter, increasing the distance from the injection point produces a negligible reduction in strength in medium as well as in fine sands. These results indicate that the procedure adopted provides fairly uniform grouted samples. Furthermore, the good reproducibility of treated samples was verified based on the repetition of UCS tests on mineral-based grout specimens prepared in a second-phase-test programme under identical conditions adopted in the first phase (see fig. 8).

Unconfined compression strengths obtained in the present research were compared with those reported by other authors on Fontainebleau sand (D_{50}= 0.22 mm), grouted with silicate and mineral grouts (Delfosse-Ribay et al. 2004, 2007). The higher unconfined compressive strength measured by these authors on the sand treated by mineral grouts (on average 2 MPa) can be largely ascribed to the higher strain rate selected for UCS tests (14%/min), which can lead to an overestimation of q_{UCS} .

The authors performed drained triaxial compression tests in the context of previous research (Porcino et al., 2012) which addresses the basic behaviour of grouted sand samples under static loading. The results obtained confirmed that the linear peak strength envelopes of chemically grouted sand samples are practically parallel to that of uncemented sand with an apparent cohesion intercept, $c^{'}$=29 kPa (silicate grout) and 73 kPa (mineral based grout). The internal peak friction angle was practically the same for treated and untreated sands and had a value close to 37° irrespective of the adopted grouts.

Shear wave velocity and small-strain shear modulus

Shear wave velocity measurements can be used as a valuable tool to verify the efficiency of in-situ ground improvement, even for lightly grouted deposits. The advantage of using such measurements is that they can be performed both in situ and in laboratory.

For reasons of comparison and to obtain base-line values for quantifying the improvement of the dynamic properties due to grouting, bender element tests were also conducted on untreated sand specimens. Results obtained (Figure 9) evidenced the influence of grout features on V_s values with higher shear wave velocities for sands treated with mineral-based grouts, with respect to those grouted by silicate solution. At a reference effective confining stress of 100 kPa, average values of V_s were 660 m/s and 410 m/s, for the sand grouted with MG1 and MG2, respectively. Significantly lower vales of V_s were gathered for sand improved with sodium silicate solution, namely 243 m/s.

The small strain shear modulus (G_0) of tested samples was calculated from V_s by using the elastic relationship:

$$G_0 = \rho \cdot V_s^2 \quad (1)$$

ρ being the total mass density of the sample at the end of consolidation.

The results for grouted specimens of the two tested sands are presented in figure 10. Experimental data depict the influence of mean effective stress ($p^{'}$) on G_0 values; the small strain stiffness increases as the mean effective stress increases. However, it is evident that sand samples treated with mineral grouts exhibit a rate of increase which is significantly lower compared to that of the untreated sand. On the contrary, samples treated by silicate grout show a trend of G_o with $p^{'}$ that is quite similar to that of untreated sand. The results shown in fig. 10 are typical of the general trend observed for cement-grouted specimens, where the strength of the bonds between sand grains and grout modifies the behaviour of the grouted sand with respect to effective confining stress, and a small influence of the confining pressure on the initial shear modulus is observed for highly cemented sands (Acar and El-Tahir 1986, Baig et al. 1997, Fernandez and Santamarina, 2001, Lee et al., 2008). Conversely, for lightly grouted sand specimens (TS+silicate), the soil response is "stress-controlled" approaching the power relation that characterizes freshly reconstituted granular materials.

In order to better visualise the effect of grouting on small strain shear behaviour of sands, the results were expressed in terms of an improvement factor (I_f) (Dano and Hicher 2003;.Dano et al. 2004, Delfosse-Ribay et al. 2004), defined as the ratio of the shear modulus after grout treatment on its value before treatment.

$$I_f = \left(\frac{G_{0,grouted\ sand}}{G_{0,ungrouted\ sand}} \right) \qquad (2)$$

Improvement ratios are generally dependent on the features of the grout, mean effective stress and soil characteristics. Therefore, improvement ratios of small strain shear modulus for the sands treated by different chemical grout are reported in table 2.

It is apparent that the average I_f values, evaluated at a reference effective stress of 100 kPa, are greater than 9 for sands grouted with MG1 and range from 3.5 to 6 for sands grouted with MG2. On the other hand, for sands treated with sodium silicate solution, which have weaker unconfined compression strengths than the other two grouts, average improvement ratios less than 2 have been obtained.

Table 2 also evidences the effect of grain-size on initial shear moduli of treated sands with higher G_0 values in the case of finer sands. In the samples with smaller grain-size, there would be more contact points, which the grout would enlarge. This was also noted for cement-grouted specimens by several authors (Chang & Woods, 1992; Yang & Salvati, 2010) who found that grain-size (D_{10}) and uniformity features of the treated sand (C_u) both influenced the effect of cementation.

Shear moduli and improvement factors measured in the present study from bender element tests were compared to the results gathered by other authors on chemically grouted sand specimens (table 2), for the closest available density index of the sand skeleton and grain size characteristics of tested sand. I_f values of G_0 gathered by Delfasse-Ribay et al. (2004) through resonant column tests carried out on dense Fontainebleau sand stabilized by mineral based grouts, are consistent with those obtained in the present study for TSF+ MG2 while they are significantly lower than those measured for MG1. Part of the observed differences can be attributed to the difference in the test apparatus used for dynamic moduli assessment. In fact it is recognised that shear strains induced in tested samples by bender elements lie below the lower strain induced by the resonant column. A similar behaviour has been observed by other researchers on cement-grouted sands (i.e.Baig et al., 1997; Pantazopoulos &Atmatzidis, 2012). The results obtained in the present investigation on silicate grouted sand (fig. 8) correspond well with those reported by Maher et al. (1994) on Ottawa sand+ silicate grout (table 2).

Following the approach proposed by Saxena et al. (1988), which assumes an independent role of the granular skeleton and the grout matrix, the maximum shear modulus of grouted sand can be expressed as the summation of modulus of untreated sand ($G_{0,ungrouted\ sand}$) and the increase in modulus due to treatment effects (ΔG_0):

$$G_{0\ (grouted\ sand)} = G_{0(ungrouted\ sand)} + \Delta G_0 \quad (3)$$

In general, ΔG_0 values depend on type of grout, degree of cementation and effective confining pressure.

Figure 11 presents the relation between ΔG_0 and q_{UCS} values, where ΔG_0 was measured at a reference effective mean stress of 100 kPa. While there is inevitably some scatter of the data, it appears that a unique linear relationship between ΔG_0 and q_{UCS} (expressed in MPa) can be proposed for the considered tested materials, and density state of the sands:

$$\Delta G_0 = 908 \cdot q_{UCS} \quad 4)$$

The R^2 value, which is a measure of the validity of regression fit, is about 0.92.

Similar correlations between ΔG_0 and q_{UCS} for cemented sands, were reported by other authors (i.e. Lee et al. 2008).

Hydraulic properties of grouted sands

The adopted chemical solutions significantly modify the permeability characteristics of pure sand (Figure 12). Lower values of hydraulic conductivity were measured for sand stabilized with mineral grouts (k $=10^{-11}$ m/s - 10^{-10} m/s) with respect to silicate-based grout specimens (k$=10^{-9}$ m/s). The influence of grain-size of sand on hydraulic properties of treated sand doesn't appear to be significant for the grouts and the sands adopted in the present investigation.

Conclusions

An experimental investigation was carried out with the aim of exploring the mechanical and hydraulic properties of two sands treated with mineral-based grouts, namely MG1 and MG2. Reaction in soil grouted by mineral-based grouts leads to the formation of silicate crystals which are strong and insoluble, resulting in a stronger end product which is more resistant to most of the usual aggressive environments.

It was verified that the system adopted allows the preparation of "high quality" multiple (four) grouted sand samples from a single column, with good features of uniformity and reproducibility. The behaviour of the sands treated by mineral grouts, in terms of strength, initial stiffness and permeability, was also compared with that observed on a more traditional silicate based solution with inorganic reagent.

On the basis of test results performed on both untreated and treated sands, the following conclusions can be advanced:

1.Strength properties of grouted sands

The unconfined compressive strength of sands treated by mineral based grouts increased along with curing time of grouted samples. Adequate curing time (i.e. 28 days) assures that the largest part of the strength gain of the grouted sand occurred. The unconfined compression strength of grouted fine sand specimens, evaluated at the curing time of about 28 days can range from 650 kPa (mineral grout MG2) up to 900 kPa (mineral grout MG1). The use of sodium-silicate based grout resulted in a small increase in strength with q_{UCS} values in the range of 80 kPa to 150 kPa for medium and fine Ticino sand, respectively. The results indicate that, whatever type of grout is considered, higher strengths are expected for finer grained sands, which have a higher specific surface than coarser sands and provide more bonding surface for the grouts.

2. Behaviour of grouted sands at small strains from Vs measurements

In the very small strain domain, the effect of cementation due to treatment leads to higher values of small strain shear modulus measured by bender element tests with respect to untreated sands. Improvement ratios (I_f), defined as the ratios of the initial shear modulus after grouting on its value before treatment, depend on grout type, particle size of tested sand and effective confining stress.

Lightly grouted sands by sodium silicate render average improvement ratios at a reference effective mean stress of 100 kPa ranging from 1.1 to1.6, whereas significantly higher values were gathered for sands grouted with mineral grouts, in the range of 3.5-6 for MG2 and even greater than 9 for MG1 type. The results indicate that particle size influences the small-strain shear modulus of grouted sands, with higher G_0 values in the case of finer sands.

The influence of effective confining stress (i.e. in situ depth) on G_0 values is less pronounced for mineral-based grouted sands (i.e. higher cementation level) than for sand grouted with silicate grout. This observation is consistent with the conclusions from experimental results on cement-treated sands reported in literature by other authors.

Small strain shear modulus increment, ΔG_0, from treated to untreated sand specimens, evaluated at a reference effective mean stress of 100 kPa, was correlated with the corresponding q_{UCS} values, obtaining a practically unique relationship, regardless of the type of grout and grain size of sand.

Comparative results from shear wave velocity measurements by bender element tests in triaxial apparatus, highlight that such measurements can be used as a valuable tool to verify the efficiency of in-situ ground improvement, even for lightly grouted sands.

3. Hydraulic properties of grouted sands

Hydraulic properties of the tested sands were significantly modified by chemical grout treatment. The permeability coefficient reduced by up to $k = 10^{-9}$ m/s with silicate-based grouted specimens and up $k = 10^{-11}$ m/s for sand stabilized with mineral grouts. It may be noted that the effect of grain-size on hydraulic properties of the grouted sands was relatively insignificant.

References

Acar, Y. and El-Tahir, E., 1986. Low strain dynamic properties of artificially cemented sand. *Journal of Geotechnical Engineering*, ASCE, 112(11), 1001–1015.

Aiban, S.A. ,and Zindarcic, D., 1989. Evaluation of the flow pump and constant head techniques for permeability measurements. *Geotechnique*, 39(3), 655 –666.

ASTM D4219-08. Standard Test Method for Unconfined Compressive Strength Index of Chemical-Grouted Soils.

ASTM D4320 / D4320M-09. Standard Practice for Laboratory Preparation of Chemically Grouted Soil Specimens for Obtaining Engineering Parameters.

Ata, A. ,and Vipulanandan, C., 1998. Cohesive and adhesive properties of silicate grout on grouted-sand behavior. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE , 124(1), 38-44.

Baig, S., Picornell, M., and Nazarian, S., 1997. Low strain shear moduli of cemented sands. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 123(6), 540–545.

Brignoli, E.G.M., Gotti, M., and Stokoe, K.H.,1996. Measurement of shear waves in laboratory specimens by means of piezoelectric transducers. *Geotechnical Testing Journal*, GTJODJ, ASTM, 19(4), 384-397.

Chang, T.S., Woods, R. D., 1992. Effect of particle contact bond on shear modulus. *Journal of Geotechnical Engineering Division*, 118(8), 1216-1233.

Chang, T.S., Woods, R. D., and Li, N. H., 1990. Preparation of grouted sand specimens for dynamic testing". *ASTM, Geotechnical Testing Journal*,GTJODJ, 13(3), 235-242.

Christopher, B.R., Atmatzidis, D. K. ,and Krizek, R.J., 1989. Laboratory testing of chemically grouted sand. *Geotechnical Testing Journal, ASTM,* 12(2), 109-118.

Clough, G.W. , Kuck, M., and Kasali, G., 1979. Silicate-stabilized sands. *Journal of Geotechnical Engineering Division, ASCE*, 105(1), 65-82.

Dano, C., and Hicher, P.Y., 2003. Behavior of uncemented sands and grouted sands before peak strength. *Soil and Foundation*, 43(4), 13-19.

Dano, C., Hicher, P.Y., and Tailliaz, S., 2004. Engineering properties of grouted sands. *Journal of Geotechnical and GeoEnvironmental Engineering, ASCE,* 130(3), 328-338.

Diefenthal, D.C., Borden, R.H., Baker, W.H., and Krizek, R.J., 1979. Strength and stiffness of silicate grouted sand with different stress histories. *Geotechnical Testing Journal, GTJODJ*., ASTM, 2(4), 200-205.

Delfosse-Ribay, E., Maigre, I.D., Cabrillac, R., and Gouvenot, D.,2004. Shear modulus and damping ratio of grouted sand. *Soil Dynamics and Earthquake Engineering*, 24(6), 461-471.

Delfosse-Ribay, E., Maigre, I.D., and Cabrillac, R., 2007. Comparison of creep behaviour and fatigue behaviour of grouted sand. *Soils and Foundations*, 47(2), 185-194.

Fernandez, A., and Santamarina, J. C., 2001. The effect of cementation on the small strain parameters of sands. *Canadian Geotechnical Journal*, 38(1), 191-199.

Gallagher, P.M., Pamuk, A., and Abdoun, T., 2007. Stabilization of liquefiable soils using colloidal silica grout. *Journal of Materials in Civil Engineering*, ASCE, 19 (1), 33-40.

Gouvenot, D., 1998. State of the art in European grouting. Ground Improvement., 2(2), 51-67.

Jovicic, V., Coop, M. R., and Simic, M., 1996. Objective criteria for determining G_{max} from bender element tests, *Geotechnique*, 46 (2), 357–362.

Ismail, M.A., Joer, H.A., and Randolph, M.F., 2000. Sample preparation technique for artificially cemented soils. *Geotechnical Testing Journal*, *ASTM,* 23(2), 171-177.

Kaga, M., and Yonekura, R., 1991. Estimation of strength of silicate-grouted sand. *Soils and Foundations*, 31(3), 43-59.

Karol, R.H., 2003. *Chemical grouting and soil stabilization*, New York: Marcel Dekker.

Krizek, R.J., BenItayf, M.A., and Atmatzidis, D., 1985. Effective stress-strain-strength behavior of silicate-grouted sand. In: H. Baker, ed. *Proceedings. of Conf. on Grouting in Geotechnical Engineering.* W., sponsored by the Geotechnical Engineering Div. of the ASCE; in cooperation with ASCE/AIME Underground Technology Research Council, Louisiana Section, ASCE and Louisiana Section, ASCE and New Orleans Branch, ASCE, February 10-12, 1982, New Orleans, Louisiana, United States, 482-497.

Lee, J.S., and Santamarina, J.C., 2005. Bender elements: Performance and signal interpretation. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 131(9), 1063-1070.

Lee, M.J., Choo, H., Choi, S.K., Lee, J.S. and Lee, W., 2008. Effect of cementation on small-strain shear modulus of sand. In: Burns, Mayne and Santamarina, eds. *Proceedings the fourth International Symposium on Deformation characteristics of Geomaterials, IS-Atlanta 2008*, 21-24 September 2008, Atlanta, Georgia, USA, 275-281.

Maher, M.H.,Ro, K. S., and Welsh, J.P., 1994. High strain dynamic modulus and damping of chemically grouted sand. *Soil Dynamic sand Earthquake Engineering*,13, 131–138.

Mohsin, A.K.M., and Airey, D.W., 2003. Automating G_{max} measurement in triaxial tests. In: Di Benedetto et al., ed. *Proceedings 3rd International Symposium on the Deformation Characteristics of Geomaterials*, , Lyon, France, 73-80.

Pantazopoulos, I.A. and Atmatzidis, D.K., 2012. Dynamic properties ofmicrofine cement grouted sands. *Soil Soil Dynamic sand Earthquake Engineering* 42, 17–31.

Pellegrino, G., 1999. Soil improvement technologies for tunneling: selected case histories. Presented at *ASCE Met Section Spring 1999 Geotechnical Seminar, State-of-the-Art Technology in Earth and Rock Tunnelling*, New York, May 26-27.

Porcino, D., Marcianò, V., and Granata, R., 2011. Undrained cyclic response of a silicate-grouted sand for liquefaction mitigation purposes. *Geomechanics and Geoengineering an International Journal*, 6(3),155-170.

Rodriguez, J.A.D., Izarraras, V.M.A., Bandini, P., and Molina, J.A.L., 2008. Cyclic strength of a natural liquefiable sand stabilized with colloidal silica grout. *Canadian Geotechnical Journal*, 45, 1345 – 1355.

Saxena, S.K., Avramidis, A.S., Reddy, K.R., 1988. Dynamic moduli and damping ratios for cemented sands at low strains. *Canadian Geotechnical Journal*, 25(2), 353-368.

Schwarz, L.G., and Krizek, R.J., 1994. Effect of preparation technique on permeability and strength of cement-grouted sand. *Geotechnical Testing Journal*, ASTM, 17(4), 434-443.

Sembenelli, G., and Angeloni, G., 1992. Prove di permeabilità a portata controllata. Technical Note, *Italian Geotechnical Journal*, 26(3) 195-197.

Spencer, L.M., and Rix, G.J., 2008. Small strain dynamic properties of colloidal silica gel and sand mixtures. In: Burns, Mayne and Santamarina, eds. *Proceedings Fourth International Symposium on Deformation Characteristics of Geomaterials*. Altanta (USA), 299 – 305.

Tailliez, S., 1998. Étude expérimentale du comportement mécanique des sols granulaires injectés. Thesis (PhD), Ecole Centrale de Paris (in French).

Tornaghi, R., Bosco, B., and De Paoli, B., 1988. Application of recently developed grouting procedures for tunnelling in the Milan urban area. Paper Presented at the *Fifth International Symposium TUNNELLING 88*, 18-21 April 1988, London.

Tsukamoto, Y., Ishihara, K.,Umeda, K., and Enomoto, T., 2006. Cyclic resistance of clean sand improved by silicate-based permeation grouting. *Soils and Foundations*, 46, 233–245.

Viggiani, G., and Atkinson, J.H., 1995. Interpretation of bender element tests. *Geotechnique*, 45(1), 149-154.

Yang, L., and salvati, L., 2010. Small strain properties of sands in the different cement types. *Fifth International Conference on recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics* and *Symposium in Honor of Professor I.M.Idriss*. May 24-29 2010, San Diego, California, Paper No 1.05a.

Zhang, M., Takahashi, M. and Esaki, T., 1998. Laboratory measurement of low-permeability rocks with a new flow pump system. In: *Proceedings, 21st, Scientific basis for nuclear waste management*, *Materials Research Society Symposium*, 506, 889-900.

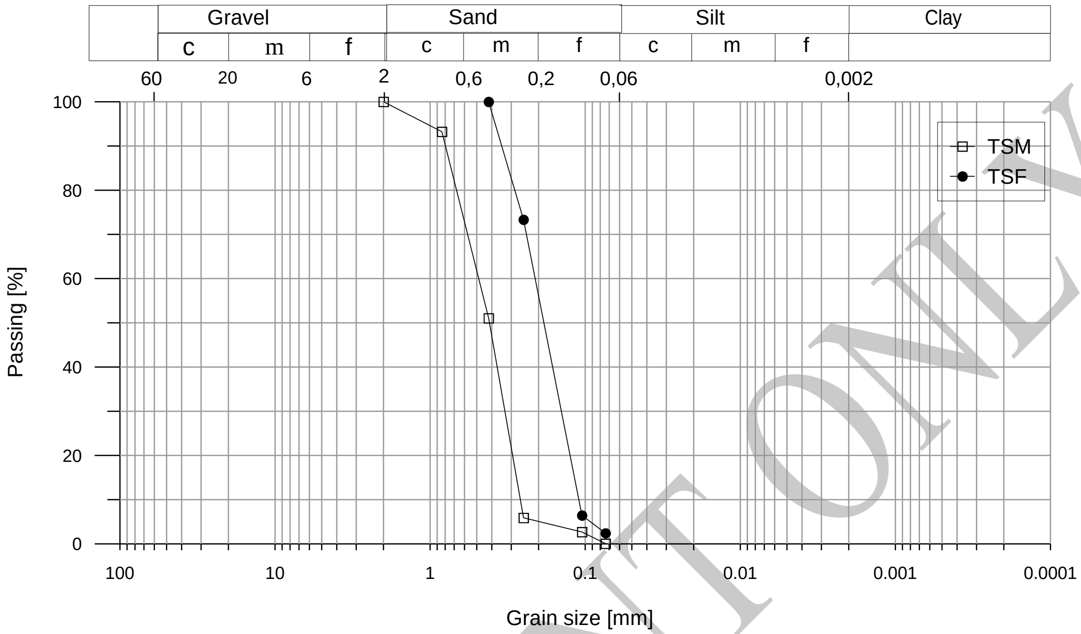
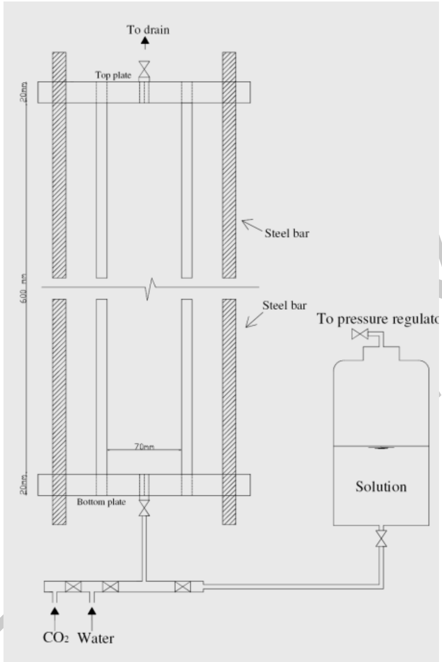


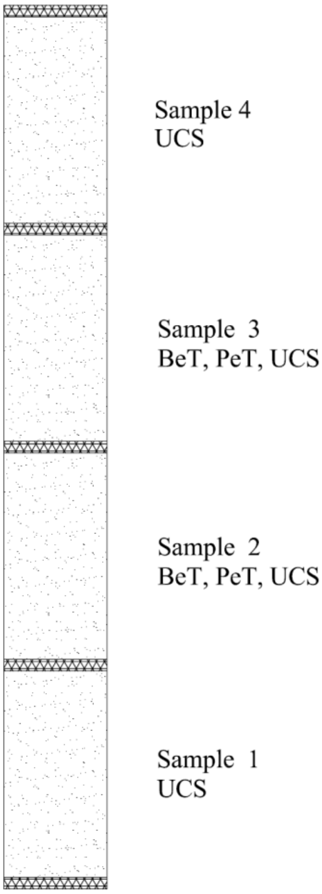
Figure.1. Grain-size distribution curves of tested sands

(a)



(b)

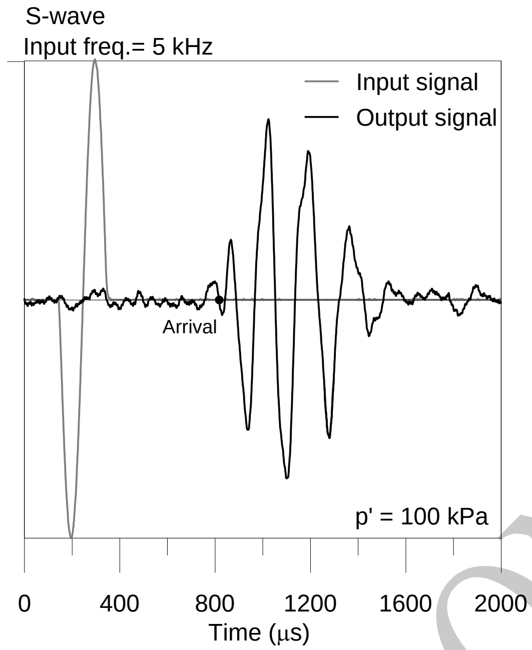
Figure. 2. System adopted for the preparation of grouted sand specimens



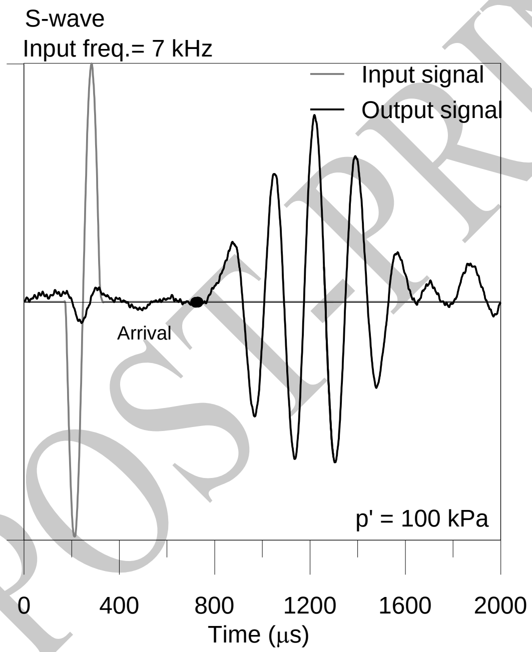
(a)

(b)

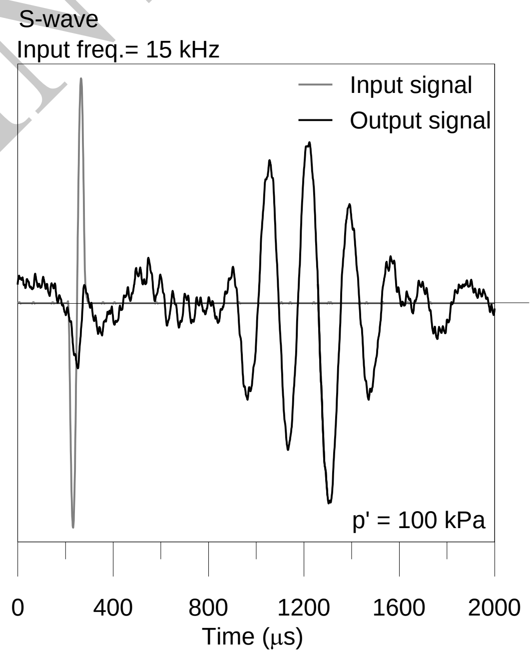
Figure. 3. Multiple grouted sand specimens resulting from a single column (Ticino fine sand+ mineral grout)



(a)



(b)



(c)

Figure. 4 Typical S-wave signals propagated through triaxial specimens: (a) TSM, (b) and (c) TSM treated with sodium silicate grout

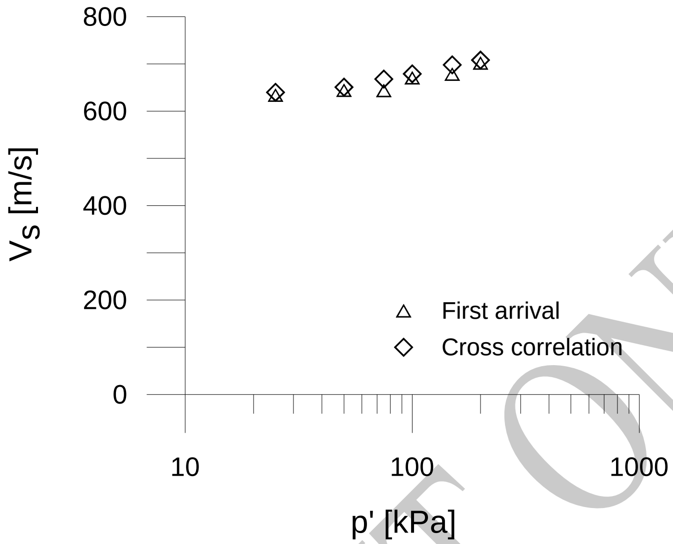


Figure. 5. Comparison between V_s values predicted from two interpretation methods for TSM treated with MG1 mineral grout

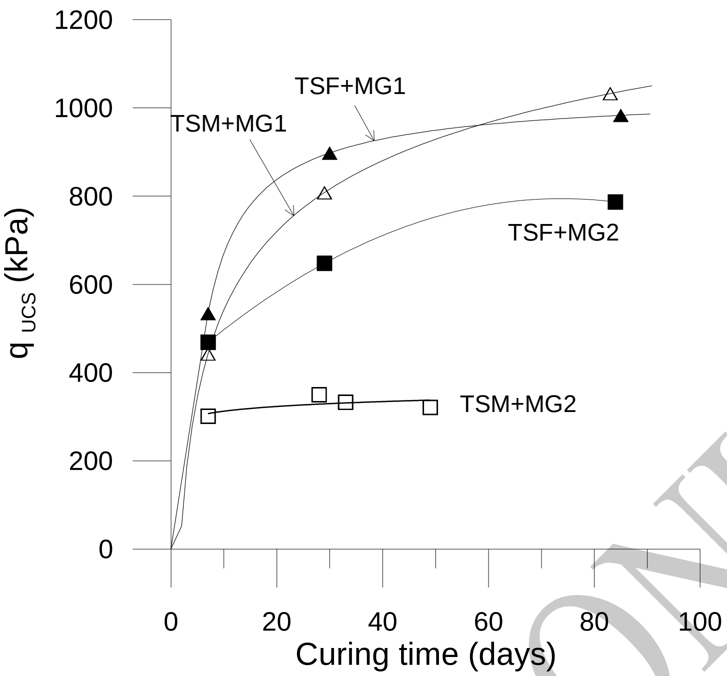


Figure. 6. Influence of curing time on unconfined compressive strength of Ticino sand grouted with mineral gouts

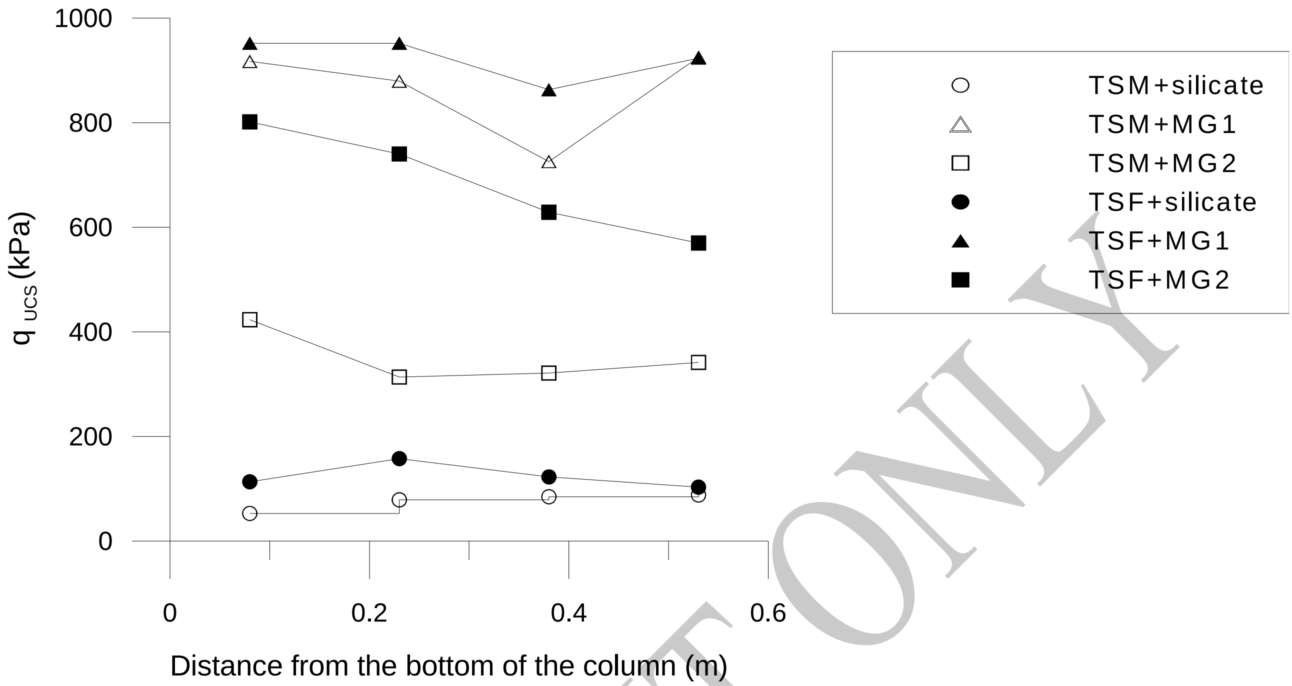


Figure. 7. Influence of grain size of sand and grout type on unconfined compressive strength evaluated at t_{curing}=3 days. (silicate) and 30 days (mineral grouts)

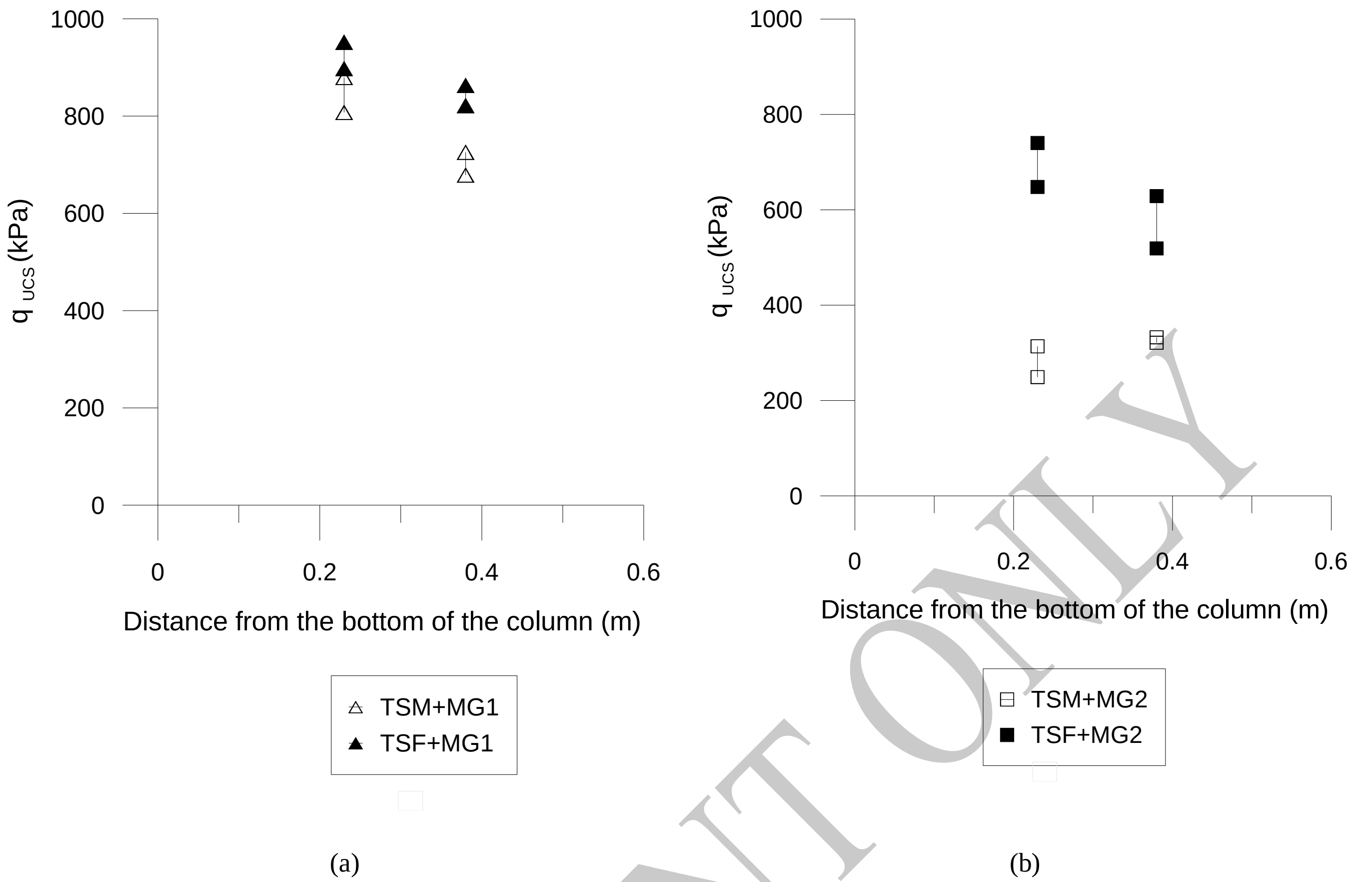


Figure. 8. Repetitiveness of test results gathered from sand specimens grouted with mineral grouts: (a) MG1 and (b) MG2. (t_{curing}=30 days)

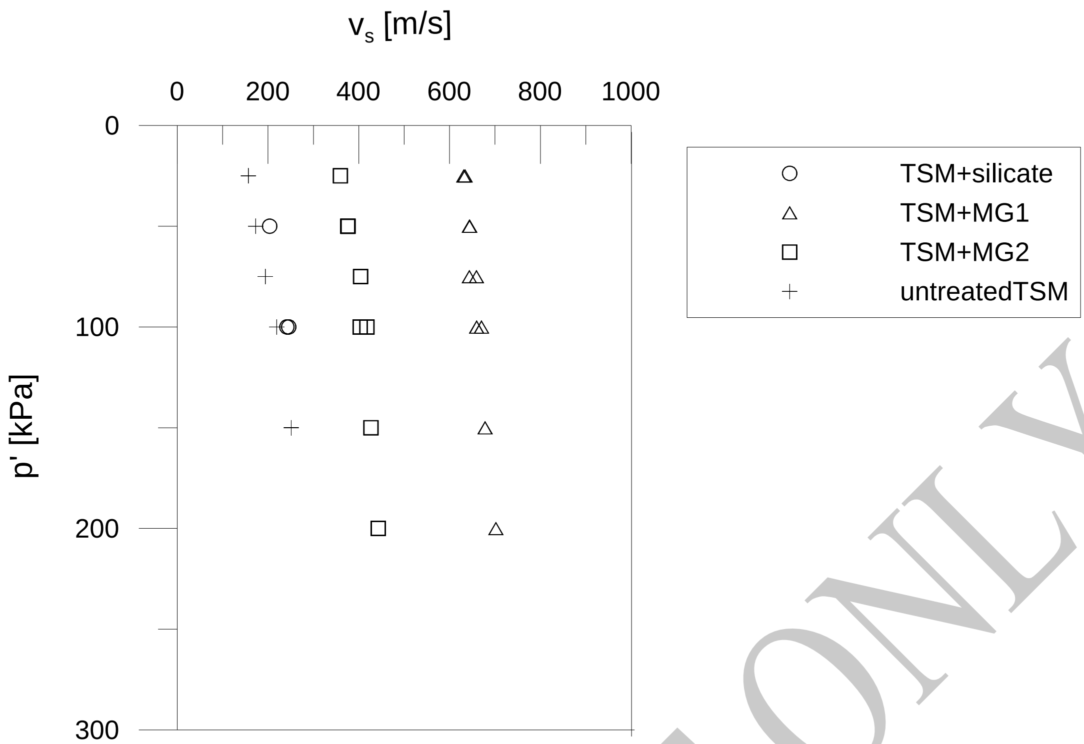
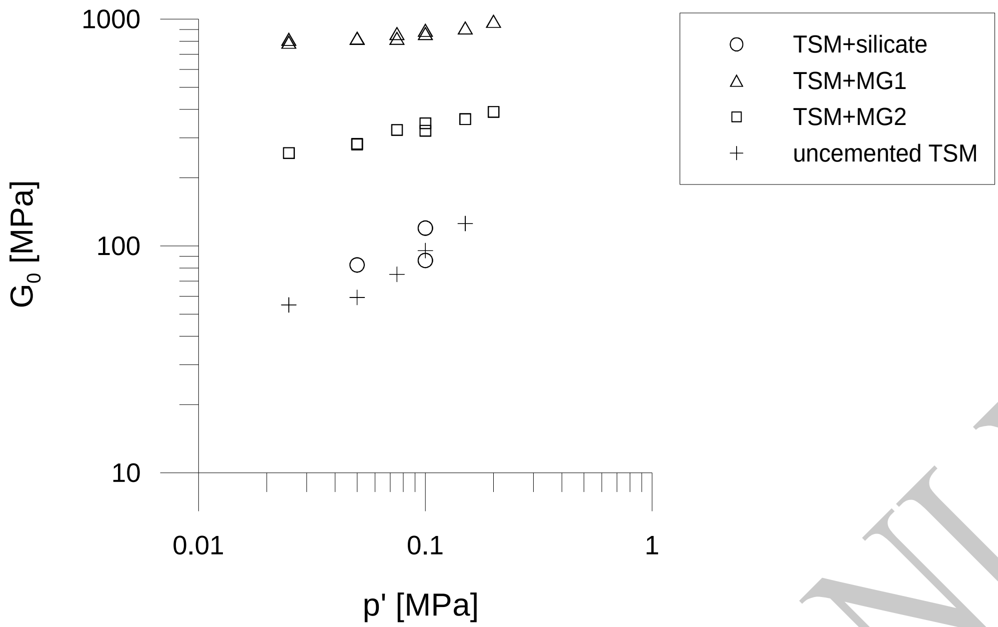
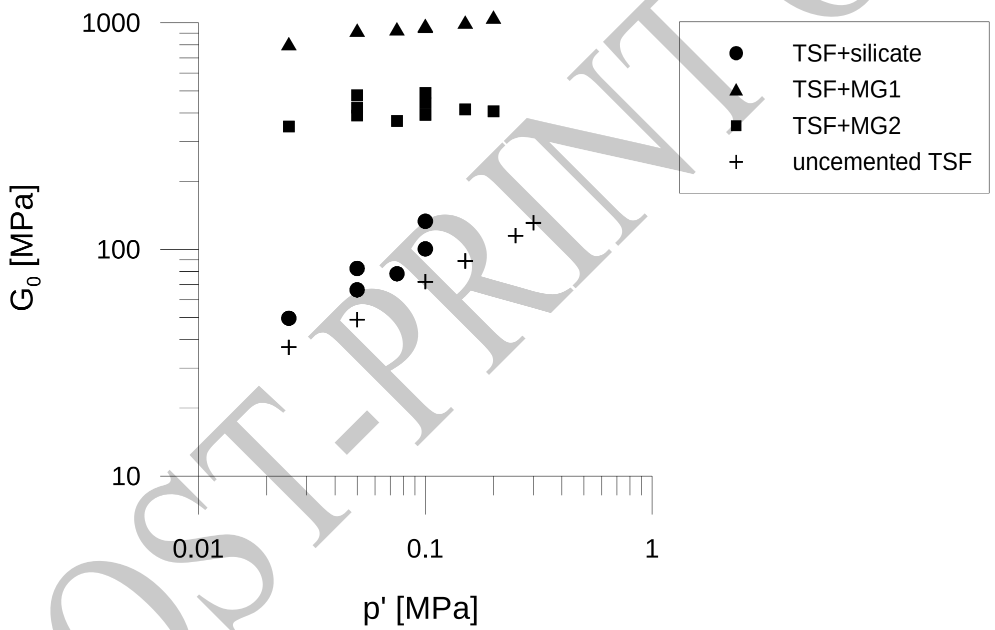


Figure 9. Variation of shear wave velocity with mean effective stress for TSM treated with different grouts



(a)



(b)

Figure. 10. Influence of mean effective stress on dynamic shear modulus of grouted sand specimens: (a) TSM+grouts; (b) TSF +grouts

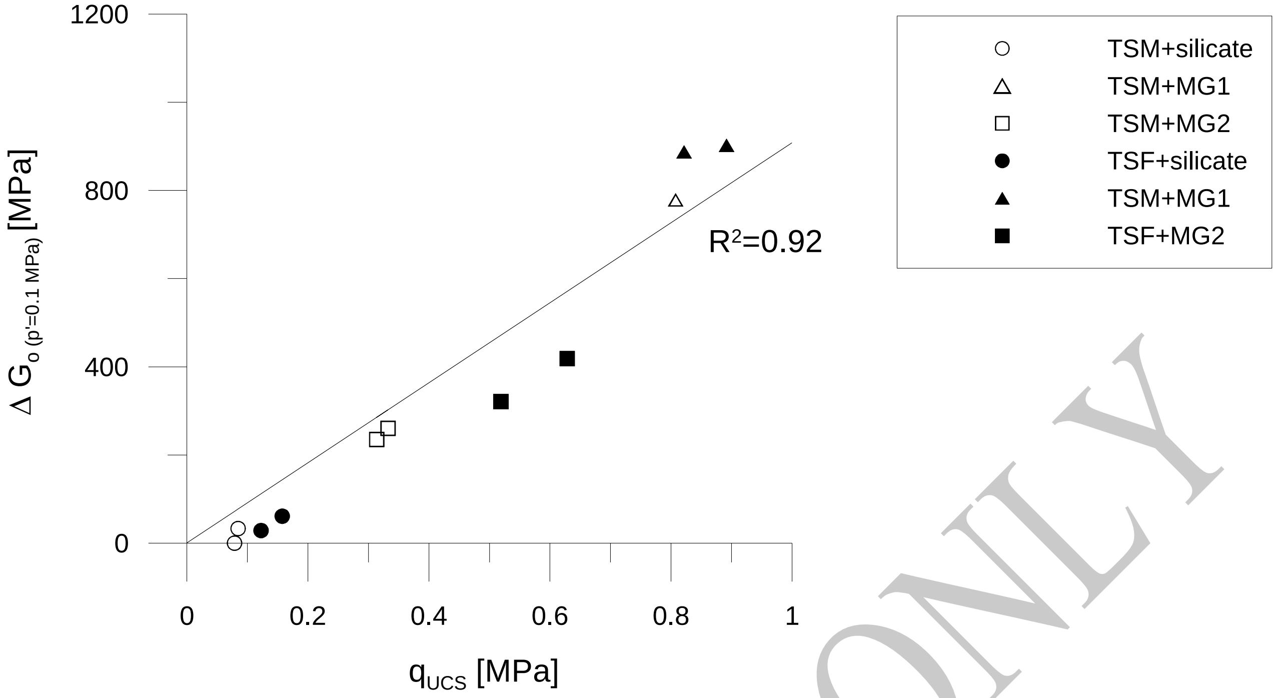


Figure.11. Relation between ΔG_0 and unconfined compressive strength for Ticino sands treated with different grouts.

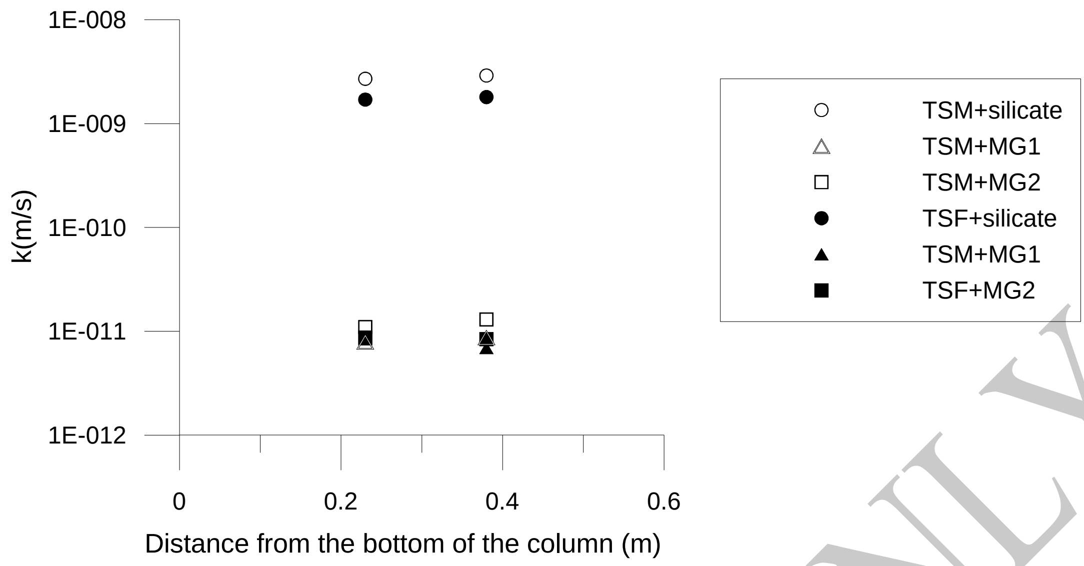


Figure. 12. Influence of grain size of sand and grout type on hydraulic features of grouted sand specimens

Table 1. Physical properties of tested sands

Sand	G_s	D_{50} (mm)	U_c	FC (%)	e_{maxx}	e_{min}
Ticino medium-oarse sand (TM)	2.68	0.415	1.86	2.42	0.942	0.624
Ticino nedium-fine sand (TSF)	2.69	0.185	1.91	0.06	0.978	0.613

Note: G_s=specific gravity; U_c=uniformity coefficient; D_{50}= mean particle diameter; FC= fine content; e_{max}, e_{min}= maximum and minimum void ratio

Table 2. Improvement factors of small strain shear modulus of sands grouted with mineral-grouts and silicate grouts.

Sand+ grout	$G_{0,\ ungrouted}$(MPa)	$G_{0,\ grouted}$ (MPa)	$I_f = \frac{G_{0,grouted\ sand}}{G_{0,un\,grouted\ sand}}$
This study; p'_c=0.1 MPa			
TSF+ mineral grout MG1	72	937	13
TSF+ mineral grout MG2	72	442	6.14
TSF+ silicate	72	117	1.62
TSM+ mineral grout MG1	95	865	9.1
TSM+ mineral grout MG2	95	335	3.5
TSM+ silicate	95	103	1.09
Delfosse Ribay et al. (2004); p'_c=0.1 MPa			
SF+ mineral grout	120	600	5
SF +silicate	120	360	3
Maher et al. (1994); p'_c=0.05 MPa			
Ottawa sand+ silicate	90	120	1.33

Note: SF= Fontainebleau sand; TSF= Ticino fine sand; TSM=Ticino medium sand
p'_c =effective confining pressure