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PERMEATION GROUTING - Development and innovation of 1D and 3D experimental tests for the analysis of the injection processes and the influence on the mechanical resistance of the grouted soil

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General Introduction

This thesis deals with the study of permeation grouting technique and the effect of injections on the mechanical characteristics of the ground treated.

This technique used either to improve the resistance and stiffness characteristics of the soil, or to reduce its permeability, and it consists in the injection of consolidating mixtures inside the ground, which permeate the voids present between the grain of the solid skeleton.

Permeation grouting injections are conducted through a valved tube, also named tube a manchettes (TAM), each valve of injection pipes is isolated and injected using a double packer; different consolidating mixtures can be used according to the granulometry, porosity and permeability of the soil.

The goals of this thesis are:

- to studying in the laboratory permeation of consolidating mixtures into the soil, with controlled characteristics of soil sample, and the mechanical characteristic developed after the treatment,
- to project and realize a machine that allows to carry out 3D injections in the laboratory and confine the soil to be injected making it like the soil present in situ.

For getting these results two macro types of experimental tests are conducted:

- column injections (1D injections),
- injections in newly developed apparatus (3D injections)

Column injection is standard test that allows to evaluate the groutability of a particular mixture within a particular granular medium; after the maturation of the injected soil in the column, it is possible to obtain specimens to be subjected to mechanical tests.

Injections carried out with newly apparatus allow to overcome the limit of the injections in the column, represented by the 1D advancement of the consolidating mixture in the ground.

These three-dimensional, large-scale injection tests, which are as similar as possible to real injections carried out in situ, may in the future form the basis for the design of permeation grouting interventions. Both from an experimental point of view, evaluating the effectiveness of injecting one or more consolidating mixtures into a given soil. And, from a theoretical point of view, in that the experimental results obtained may serve as calibration and/or validation of analytical and numerical predictive models, with which to further support the design of permeation grouting interventions with a greater level of knowledge, attempting to decrease, as far as possible, the uncertainty regarding the success of the treatment.

Chapter 1

Permeation grouting: a general review

1.1 Introduction

Permeation grouting is a grouting technique that, through the injection of consolidating mixtures into the ground and the permeation of the voids between solid grain, it makes soil similar in strength and permeability to a rock.

Since the effects of permeation grouting are not directly visible during the application of the technique in situ, different laboratory tests have been carried out over time that allow to reproduce the permeation process and allow to have specimens of treated soil on which to carry out mechanical and hydraulic tests.

An increasing number of works is nowadays available in the literature; in these works, the methods used to permeate the soil sample, the rheological characteristics of the mixtures used, the characteristics of the soil and the mechanical characteristics developed by the soil following the injection are presented.

Analyzing these studies, it is clear that the phenomenon is complex, the treatment of the soil by permeation of mixtures depends on many distinct factors.

In the first part of this chapter the information collected in literature are presented; in particular: valved tube used in the technique of permeation, factors on which depend injections, the standard injection test represented by column injection, other injection test conducted at middle scale. In second part of the chapter other characteristic elements of a permeation grouting injection are presented, which deserve to be studied to understand their influence on the injection process.

The main hypothesis of the present work is that injections have a three-dimensional course in space, so the geometry of the soil sample to be treated during the laboratory test is a factor to be considered.

As described in the second part of the chapter, for validating this hypothesis are carried out injection tests with experimental apparatus which allow to consider the three-dimensionality of the injection phenomenon. In this apparatus the manchette tube is used to conduct the injection and bentonitic sheath is present inside these machineries, these are two central elements in permeation grouting in situ.

1.2 Tube a Manchettes (TAM)

In the permeation grouting technique, valved tubes called tubes-a-manchettes (TAM) are used. These tubes, invented in 1933 by Ischy (Littlejohn G. S., 1985), allow the soil to be injected through rubber valves, placed on the tube with a fixed pitch. Several injection cycles can be conducted through each valve.

To carry out the injections, a double packer is lowered inside the TAM and is positioned at each valve to be injected.

The packer is inflated to isolate the volume of the tube at the valve, then continuing with the injection of the consolidating mixture, the pressure dilates the valve on the tube and allows the mixture to escape.

When the injection stop, the valve returns to its original shape, adheres to the tube again, preventing the mixture from flowing back into it.

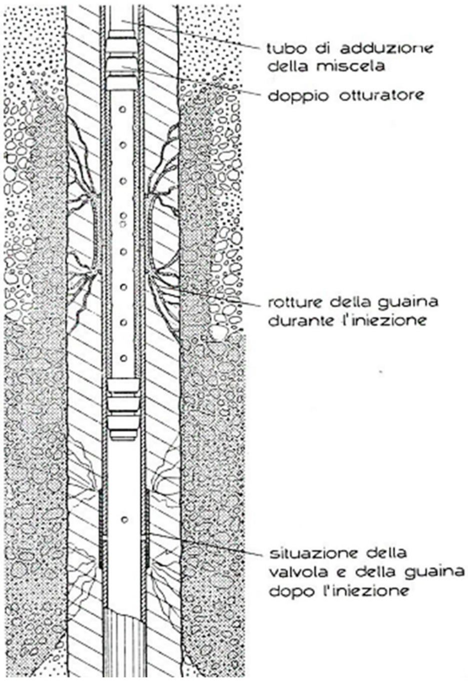

Figure 1: schematic representation of an injection through TAM using a double packer (Balossi Restelli A. 1969)

1.3 Permeation grouting: main factors

The following are the key factors that determine the applicability or non-applicability of the permeation grouting technique and that influence its performance.

Granulometry: Burwell (1958) and Incecik et Ceren (1995) relate characteristic dimensions of the soil with characteristic dimensions of the cement, used to make the mixture, based on this a preliminary evaluation of the groutability or non-groutability of a soil with respect to a given mixture.

$$N = D_{15}/d_{85}, M=D_{10}/d_{95}$$

Groutability of cement mixture is verified if N>25 and M>11 if N<11 and M<5 soil it is not grout able respect to the mixture.

R. Tornaghi (1978) drew the injectability curves of different types of consolidating mixtures in relation to the granulometry of the soil.

Akbulut S. et Saglamer A. (2002) show how the percentage of fine material (material passing through the sieve with a diameter of 0.075 mm) on the total soil mass is inversely proportional to the groutability N.

$$\boldsymbol{N = \frac{D_{10}}{d_{90}} + k_1 \frac{(W/C)}{FC} + k_2 \frac{P}{D_r}}$$

Herndon et Lenahan (1976) set a fine content of 10% as a limit to the injectability of a soil.

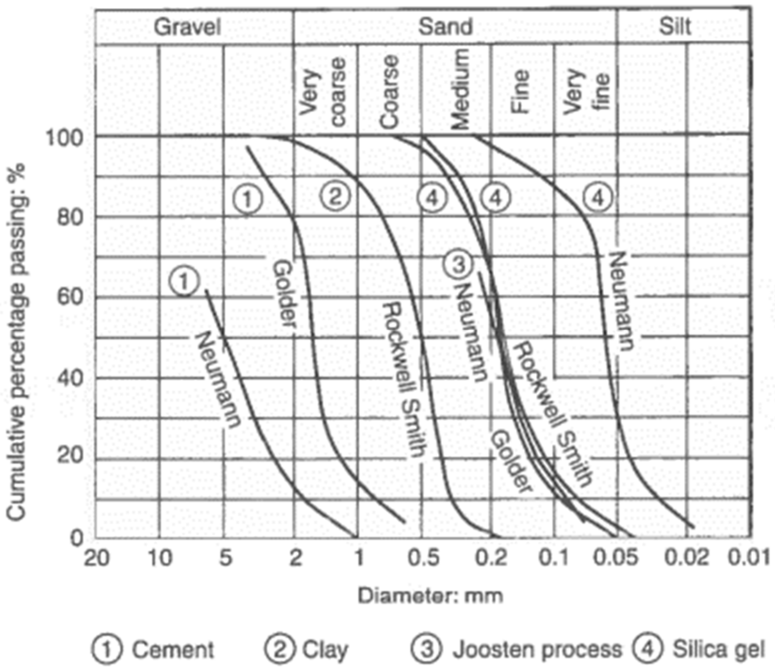

Figure 2: Penetrability limits of grouts based on the particle-size distribution of the soil (Cambefort, 1964)

Relative density (D_r): Akbulut S. et Saglamer A. (2002) and Tekin et Akbas (2010) show how the value of Dr is inversely proportional to the groutability N.

Degree of saturation of sand: Perret et al. (1997) show how the propagation of an injected mixture is better within a partially saturated soil than in a dry soil.

Water/Cement ratio: Mnif (1997), Akbulut S. et Saglamer A. (2002) and Tekin et Akbas (2010) relate the groutability parameter, N, at the W / C ratio. Proportionality is direct.

Pressure of grout: Akbulut S. et Saglamer A. (2002) and Tekin et Akbas (2010) relate groutability parameter, N, at the pressure at which the mixture is injected. Proportionality is direct.

Viscosity of the grout: de Paoli et al. (1992a) and Yoon et El Mothar (2013) show how the pore volume, penetrated by the mixture, is inversely proportional to the viscosity of the mixture itself.

1.4 Laboratory test

Injection tests in the laboratory are conducted to evaluate the groutability of a medium with respect to different mixtures. In addition to the injection test, tests are carried out to characterize the soil and the mixture used.

1.4.1 Column injection test

Column injection is the main test that allows to evaluate the possibility of injecting a consolidating mixture into a porous medium and allows to obtain samples of consolidated material in according to ASTM D4320.

The test involves the use of a column made of transparent plastic material, at the ends of the column there are two caps with a central hole and, above the lower cap and below the upper one, a metal mesh disc is placed and a gravel filter; the medium to be injected is contained inside the transparent tube. The soil inside the column is compacted until the desired relative density value is reached.

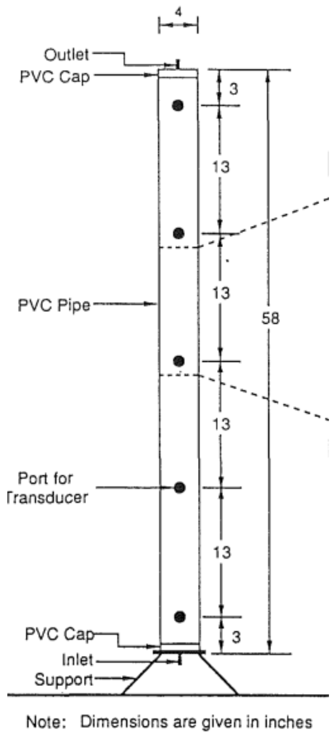

Figure 3: column schematic section, Zebovitz, S., Krizek, R. J., & Atmatzidis, D. K. (1989)

Once the column has been prepared with the soil inside, it is saturated by injecting water from the bottom upwards through a pressurized container, the drainage of the air contained in the dry soil takes place from the cap placed on the top of the column.

Subsequently the column, holding the saturated medium, is injected with consolidating mixture. The injection always takes place from the bottom up, the water contained in the soil is displaced by the mixture, comes out of the top cap, and is collected in a container through a drainage tube.

After the injection, the column is kept in a vertical position for a period and then the consolidated material is placed in water to continue maturing in a saturated environment.

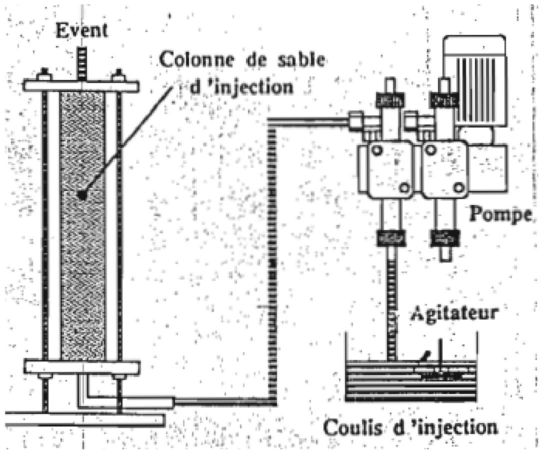

Figure 4: schematic column injection set up.

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1.4.2 Tests for soil characterization

The tests designed to characterize the granular medium which is then used during the injection tests are briefly described below.

1.4.2.1 Determination of grain size distribution

The dry sieving test allows to obtain the cumulative granulometric curve of the soil. In according to ASTM D422 the soil is dried, weighed and placed on a series of sieves, the sieves have decreasing openings that allow the passage of gradually smaller grains, under the last sieve there is a bottom that collects the material that is finer of 0.075 mm.

The sieves, containing the soil, are placed on a vibrating table that allows grains with a diameter smaller than the diameter of the sieve to fall by gravity into the lower sieve.

At the end of the vibration phase the sieves, containing the soil, are weighed in such a way as to determine the quantity by mass for each granulometric fraction of the soil. The data obtained in this way are shown in a graph with the percentage of pass-through by weight on the ordinate axis and with the value of the diameter expressed in mm on the logarithmic axis of the abscissa.

The determination of the particle size curve, and of parameters related to the particle size of the sample, is essential to evaluate the groutability or not of a mixture into a given soil.

1.4.2.2 Maximum and minimum index of voids e_{max} ed e_{min}

In according to ASTM D4253 and ASTM D4254 the maximum voids index and the minimum voids index are two standard values, inversely proportional to the density, used to calculate the relative density value, D_r.

The test to calculate e_{max} involves filling a die with granular material, depositing it through a funnel, and smoothing the ground on the die. The die filled with soil is weighed, and the density of the material is calculated.

The test to calculate e_{min} involves carrying out the operations listed for the calculation of e_{max}, a collar is then fixed on the die, a load is placed on top of the soil sample, as required by standard, and the system is placed on a vibrating table which thickens the grains that make up the soil, reducing the volume of the voids. By lowering the soil sample into the die, the volume reduction is measured and consequently the e_{min} value.

1.4.3 Rheological tests on mixture

The tests designed to characterize the mixtures used during the injection tests are briefly described below. Tests mentioned here are described in detail in API RP 13B.

1.4.3.1 Fluid density

This test makes it possible to determine the weight of a given volume of mixture. Weight can be expressed in kilograms per cubic meter (kg/m3), in pounds per gallon (lb/gal) or pounds per cubic foot (lb/ft3). The determination of the weight of a given volume of mixture is necessary for the control of the composition as regards its constancy and compliance with the requirements based on preliminary laboratory tests. The measurement accuracy must be at least 0.01 g/cm3, obtainable with the instrument commonly used for rapid and frequent checks on the cement suspensions packaging plant.

1.4.3.2 Marsh viscosity

Viscosity and stiffness are measures related to the fluidity of the mixture and its short-term evolution and serve to define the rheological behavior of the mixture itself during and immediately after the injection.

The Marsh cone is sized to allow a flow of 946 cm^3 (approximate to 1l) of water, at a temperature of 21 ° C in 26 seconds.

A graduated cylinder is used to measure the fluid coming out of the cone.

The test procedure involves plugging the mouth of the cone with a finger and pouring the mixture into the cone through the filter until it reaches the lower part of the filter, after which the finger is removed from the mouth of the cone and the time required to fill the 1l graduated cylinder is measured.

1.4.3.3 Viscosity with rotative viscosimeter type rheometer

Viscometers are centrifuge-type instruments operated either by an electric motor or manually by a crank.

The fluid is introduced into an annular space delimited by two coaxial cylinders.

The outer cylinder, or "sleeve" is spun at a constant speed (revolutions per minute). The rotation of the sleeve transmits, through the fluid, a torque which causes the internal cylinder, bob, to rotate.

A torsional spring opposes the rotation of the inner cylinder and an indicator, connected to the inner cylinder, measures its rotation.

The parts of the instrument have been sized in such a way that the value of the plastic viscosity and the “yeld point” are obtained by taking readings at rotation speeds of 300 and 600 rpm.

1.4.3.4 Filtration with filter press

The measurement of the pressure filtration value and the thickness of the "cake" of a mixture are fundamental parameters for controlling the stability of a mixture as they indicate the drainage speed of the water from the mixture itself.

The filter press consists of a cylindrical container with an internal diameter of 76.2 mm and a height of 64 mm.

Below the cylinder there is an annular support on which to place a paper filter with a diameter of 9 cm. The filtration area is equal to 45.8 m2. A tube is connected below the annular support which conveys the filtered fluid inside a graduated cylinder.

The fluid is put under pressure until it reaches the value of 7 atm, trying to reach this pressure in the shortest possible time (about 30”). The test time must be measured from the moment the pressurized air inlet valve

opens. After 30 minutes, the final volume of the filtered liquid is measured. The flow is interrupted by closing the valve that regulates the introduction of pressurized air and then, being careful, the vent valve opens. It is also practice performing intermediate readings at the following time intervals 30 '', 1 ', 2', 4 ', 8', 15 '.
For each measurement step, the volume of filtered water is noted, the height, mass and appearance of the "cake" that remains in the filter press are also noted.

1.4.4 Large scale test

The phenomenon of permeation has been replicated and studied in the laboratory even in large-scale tests and some significant tests are reported below.

Perret et al. (2000) to study the effect that the degree of saturation has on the injection of the cement mixture carried out large-scale injection tests.

Three barrels of 200 l capacity were filled with sand: the first saturated bulk sand (Sr 95%), the second partially saturated bulk sand (Sr 30%) and the third filled with alternate layers of fine and coarse material.

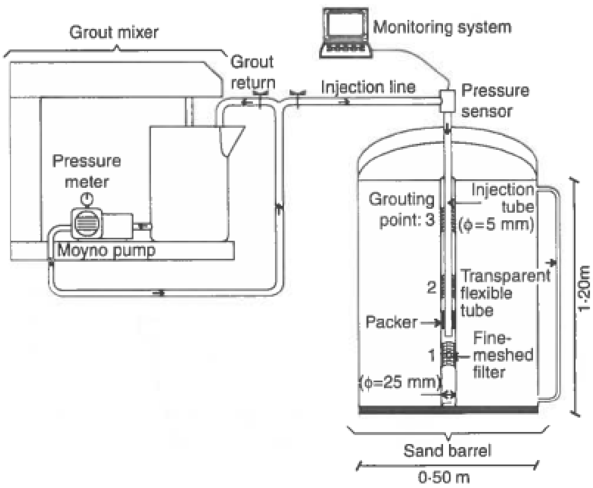

Figure 5: Perret’s large scale grouting system

The tube through which to inject is placed in the center of the barrel, four holes have been made every 30 cm along this tube and a mesh has been placed on the holes to prevent the entry of sand.

For the injection, a Moyno-type pump was used to obtain a regular flow rate of the mixture.

The material was matured inside the barrels, at the end of this process the sample was demolded, to facilitate the operation, the barrel consists of two half-sections.

Figure 6: satured alluvial sand after injection (Perret,2000)

After curing for twenty days, the specimens are cored in predetermined locations to obtain specimens for compression testing and permeability testing, these specimens continue the curing phase until thirty days from the date of injection.

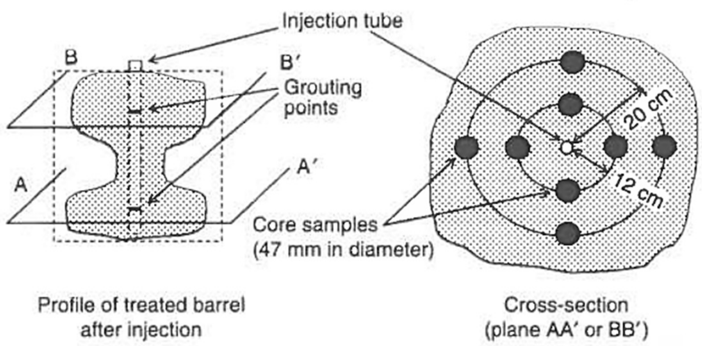

Figure 7: Schematic representation of the consolidated soil bulb and placement of the sampling points of the cylindrical specimens

The performance of mechanical tests shows that specimens obtained from partially saturated sand develop lower strength and lower elastic modulus under the same curing time and conditions.

Barrel	Grouting point and sample location	Porosity (%) Before grouting	After grouting	Decrease	Water absorption: %	$K_{before\ grouting}/K_{after\ grouting}$	28 day f'_c: MPa Results	Mean: σ	E: GPa
Saturated alluvial sand	1 12 cm	38	16	58	8	Not available	23 17 22	21(3)	24
Unsaturated alluvial sand	1 12 cm	40	17	57	10	3×10^6	11 8 13	11(2)	14
	1 20 cm	40	20	50	11·5	Not available	4 6 3	4(1)	3
Layered unsaturated sand	1 12 cm Coarse sand	51	15	70	8	6×10^8	22	22	32
	1 20 cm Coarse sand	51	20	61	11	4×10^8	17	11	23
	3 12 cm Fine sand	53	29	12	20	3×10^4	3 1 2·5	2(1)	7

Figure 8: Data obtained from conducting mechanical tests on treated soil where it is evident that samples obtained from injected saturated soil develop higher compressive strength and stiffness than those achieved by samples of partially saturated injected soil.

Bouchelaghem F. (2002) carried out two large-scale injection tests to validate an advection-dispersion-filtration model. These tests involve the injection of the cement mixture into a cylindrical container, with a diameter of 1.5 m and a height of 1.2 m, through a tube with sleeves.

The interior of the apparatus is equipped with sensors within the soil volume, displacement transducers (LVDT), interstitial pressure transducers, pressure transducers at the top and bottom of the injection tube, and on the top cover two vertical displacement transducers.

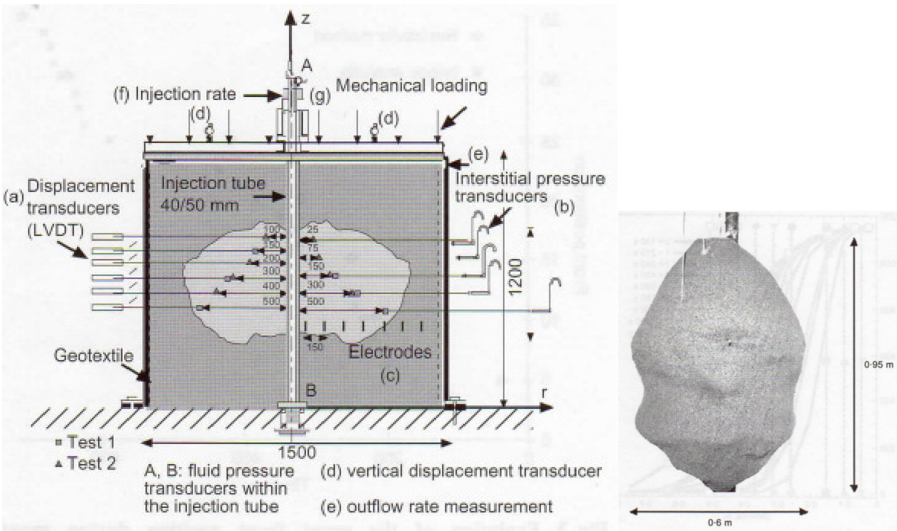

Figure 9: experimental set up (at left) and treated soil bulb (at right) (Bouchelaghem 2022)

Kim, J. S. et al. (2009), to verify the effect of viscosity and grain size on the injectability of cement consolidating mixes, they carry out two injection tests of cement mixture inside a cylindrical box, 60 cm in diameter and 70 cm high, using two different soils.

Figure 10: grouted sand bulb of the two different soils.

Farcas V. S., Popa A. & Ilies N. M. (2009) create a cylindrical box, 1.5 m in diameter and 1.3 m in height, to make an injection that would serve to validate a model. This model correlates injection pressure and mixing front speed.

Inside the soil sample there are four types of sensors: first type located in the horizontal median plane of the cylinder, a second type is a sensor registering neutral pressure along the injection, a third type on the central part of the sample, on 5 planes having different depth to register potential movements of the sand matrix and the fourth type to register vertical movement of the sample.

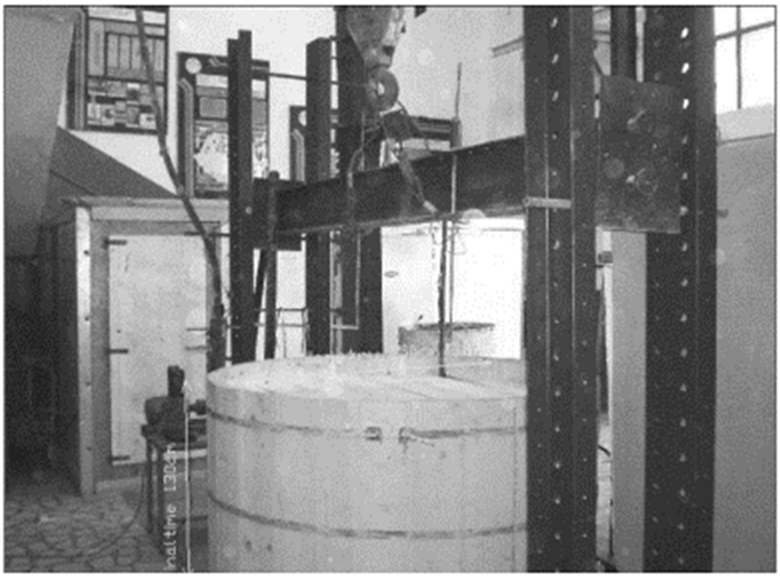

Figure 11: large scale experiment set up (Farcas et al. 2009)

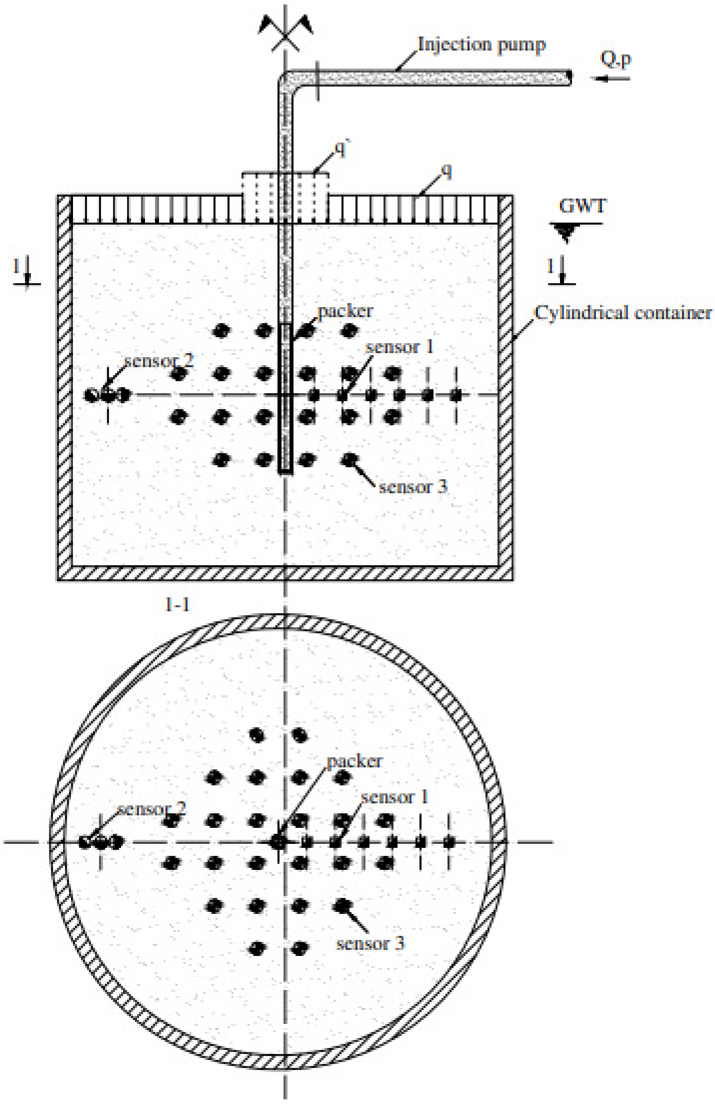

Figure 12: spatial disposition of four types of sensors (Farcas et al. 2009)

Following the experimental injection, the authors compare the time progress of the mixture in the measured soil with the time progresses obtained from the numerical model and the analytical model.

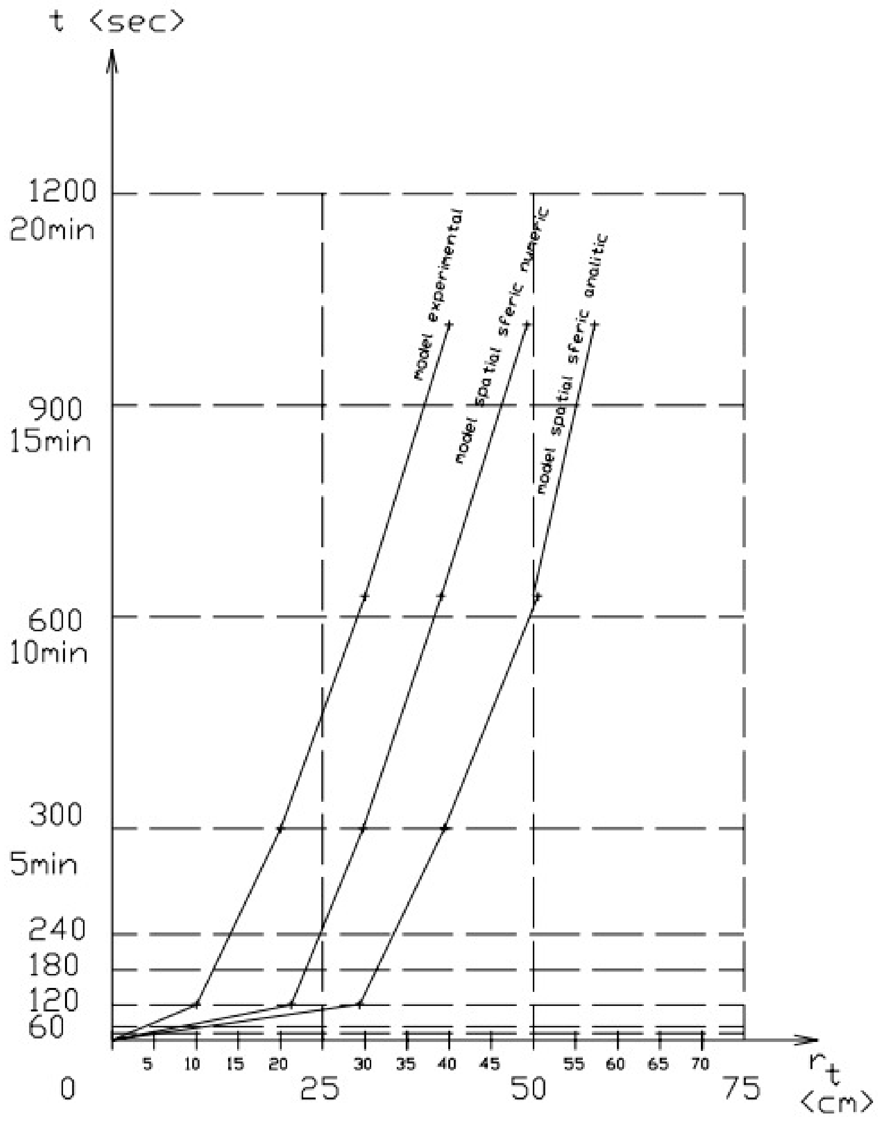

Figure 13: Graph which compares the values of the time progress of the mixing front.

Fu, Y., Wang, X., Zhang, S., & Yang, Y. (2019) realize model box made of plexiglass with a steel girder as the support member, and the geometric length, width, and height of the box are 70 cm, 45 cm, and 65 cm, respectively.

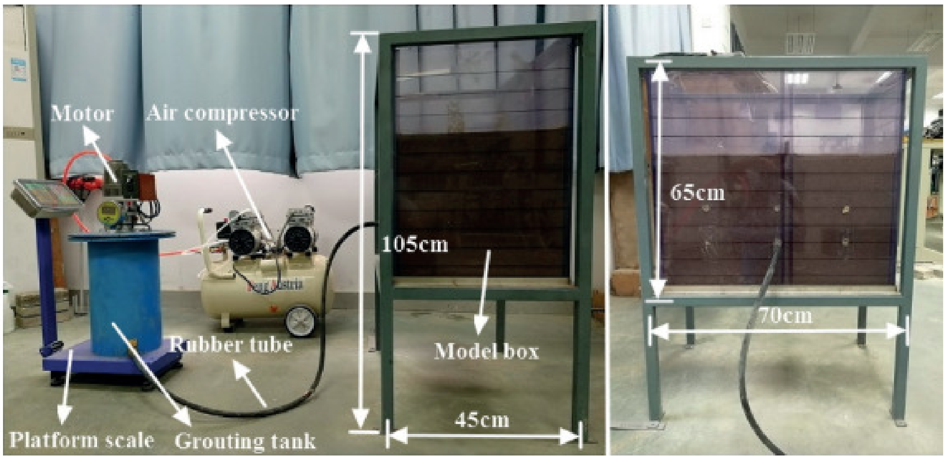

Figure 14: model box and injection apparatus (Fu, Wang, Zhang & Yang, 2019)

1.5 Apparatus for 3D injections

To study the injection of cement or silicate mixture into the ground and obtain samples of grouted sand to be used to carry out mechanical characterization tests, experimental equipment was designed and built.

This apparatus, characterized by a cylindrical shape, allow to conduct injections in a three-dimensional sample of soil, but not only. The peculiarity of the tests conducted using this equipment consists in the fact that all the elements that characterize the injection in situ are present.

They are summarized below:

- Use of a turbo-mixer to pack the consolidating mixture (in situ tool).

- Use of a piston pump to inject the mixture, this injector is equipped with a control panel to adjust the injection parameters for each single valve both in presence and remotely. At the end of the injection, it is possible to download the injected volume, flow rate and pressure data, recorded over time, on a USB memory medium (in situ tool).

- Use of an injection stand with an analogue pressure gauge mounted (as in situ) and with a digital flow meter mounted in series, capable of measuring instant flow or volume through time, used to verify the calibration of the injector itself.

- Use of a double hydraulic packer, which allows injection through the single valve of the TAM.

- Use of sleeve valved pipe.

- Presence of the bentonite sheath mixture between tubular manchette and soil and maturation of the same before conducting the injection.

- Possibility to conduct injections in dry, humid, or saturated soil, with the predisposition to carry out injections in the ground with pressurized water.

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ASTM D4253 Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table

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Chapter 2

Design of a 3D injection apparatus

2.1 Introduction

Injection tests in the laboratory are necessary to deepen the knowledge on the permeation grouting technique.

During this work we wanted to combine innovative three-dimensional injection tests of the mixture in a soil sample, to the column injection tests, which today represent the standard for evaluating in the laboratory the injectability of soils by the mixtures and for obtain samples of consolidated material.

These innovative tests make it possible to simulate permeation grouting in conditions more like those of the site compared to the one-dimensional injection carried out in the column, thanks also to the use of those in situ equipment, which in a one-dimensional and small-scale test cannot be used.

The following paragraphs present the apparatus designed to simulate permeation grouting injections in the laboratory.

2.2 Example of a real case of soil treatment with permeation grouting

This section shows a real-life case of soil treatment using the permeation grouting technique.

The technique involves the drilling of the ground in relation to the design treatment depth, which will be reached by using suitably equipped common drilling rigs and specific drilling batteries consisting of rods and casings, drilling to the design depth. The drilling fluid generally consists of water but, in some cases, depending on the purpose of the consolidation project or the characteristics of the natural ground, fluids consisting of water plus additives such as, for example, bentonite.

Once the drilling has been completed, the perforation slabs must be removed, leaving only the casing pipe in place.

The spatial distribution of the perforations, known as perforation mesh, is a function of the operations to be performed and of the radius of action, i.e., the distance covered by the injected mixture with respect to the injection point; the two most used perforation mesh geometries are triangular and square (B. B. Bosco, 2013).

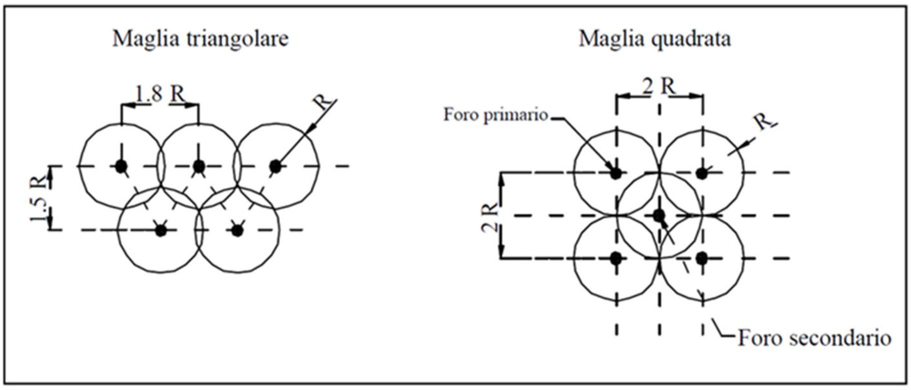


Figure 1: type of drilling mesh commonly adopted (B. B. Bosco, 2013)

This operation is followed by the laying of the casing pipe inside the casing still present in the borehole, the extraction of the casing pipe and the execution of a first injection, aimed at integrating the casing pipe with the surrounding soil or rock by injecting, from the bottom of the casing pipe, a "plastic sheath" mixture.

The injection of the consolidating mixture is carried out valve by valve using special packers that are gradually positioned at each individual valve, inside the sleeve pipe. The execution of this type of injection requires continuous monitoring of the injection parameters, which are generally defined in the design phase. These are normally recorded and diagrammed to visualise the injection progress and identify any anomalies.

The following are graphs and images from the work of Pettinaroli et al. (2019), regarding permeation grouting works carried out during the construction of the new Line 4 Milan Metro.

This work connects the Milan Linate airport with the city centre, Navigli area, and from there proceeds to the Milan San Cristoforo station, along the route there are 21 stations. For the construction of the railway tunnels, 4 TBMs were used; for the construction of the connections between the tunnels and the shafts, traditional excavation was used, and the soil was consolidated using the permeation grouting technique. Preliminary investigations were carried out at the sites where the technique was applied. Core drilling was performed, and soil samples were taken at different depths so that a stratigraphic profile could be reconstructed with the grain size curves characterising the different levels.

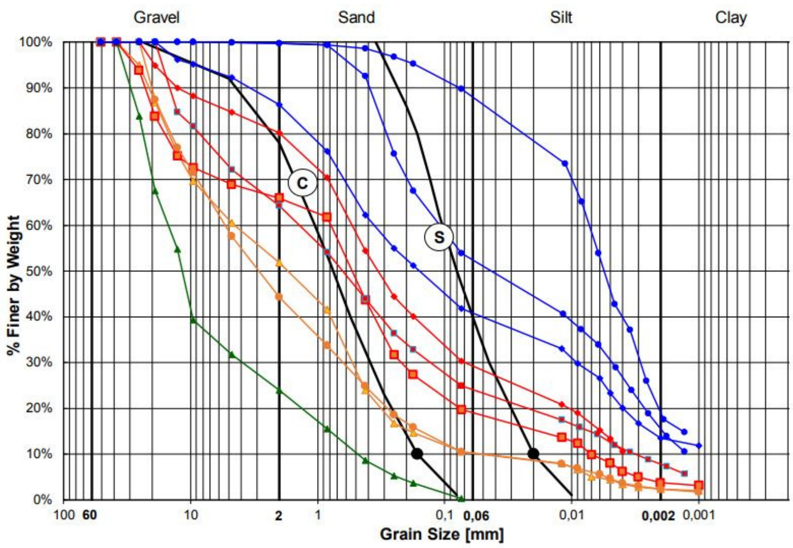


Figure 2: Grain size distribution curves

Once the characteristics of the soil are known, the recipe for the consolidating mixture capable of permeating the soil must be defined. This is usually done with successive injections, initially injecting fine cement-based mixtures, and then injecting a silicate mixture as a last pass, capable of penetrating the finer fraction of the soil and considerably reducing permeability.

Mixtures differing in composition are tested with Marsh Cone and press-filtration, to determine those mixtures that guarantee the best behaviour, set at 35-36 s at Marsh Cone and on the 75 cc of water released in 30' during the press-filtration test.

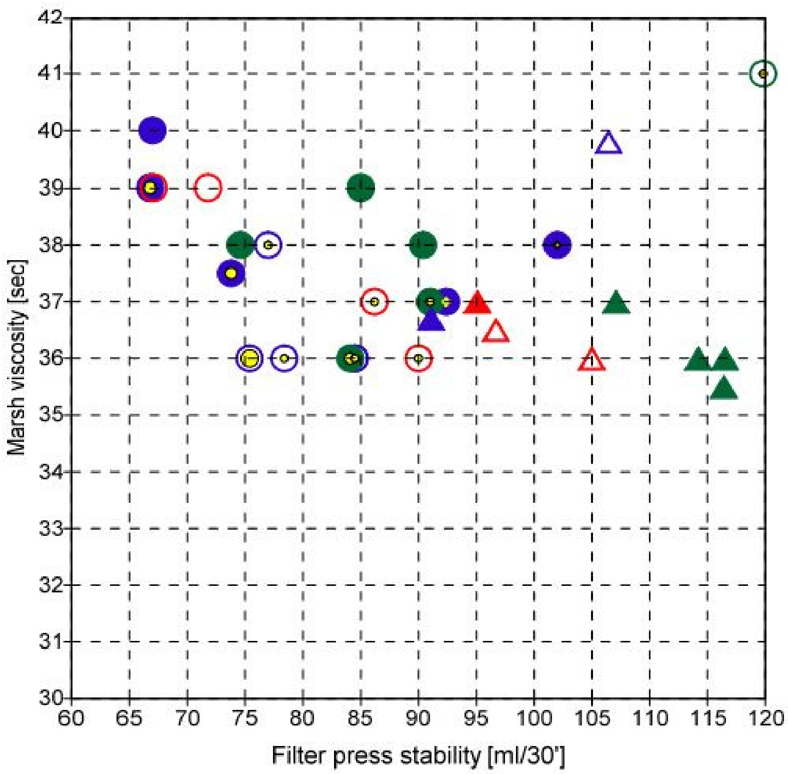


Figure 3: Tests on cement grout mixtures: Marsh viscosity vs filter press stability

The drilling is then carried out, the manchettes are placed inside the boreholes and the sheathing is poured; the behaviour of the buildings adjacent to the site where the permeation grouting is carried out is monitored through topographical surveying. The characteristics of the mixture are monitored daily, and its density, Marsh viscosity and bleeding are measured if it is a cement-based mixture, or setting time by Cup test if it is a silicate-based mixture.

Figure 4: drilling and grouting works, respectively on the left and on the right. (Pettinaroli A. et al., 2019)

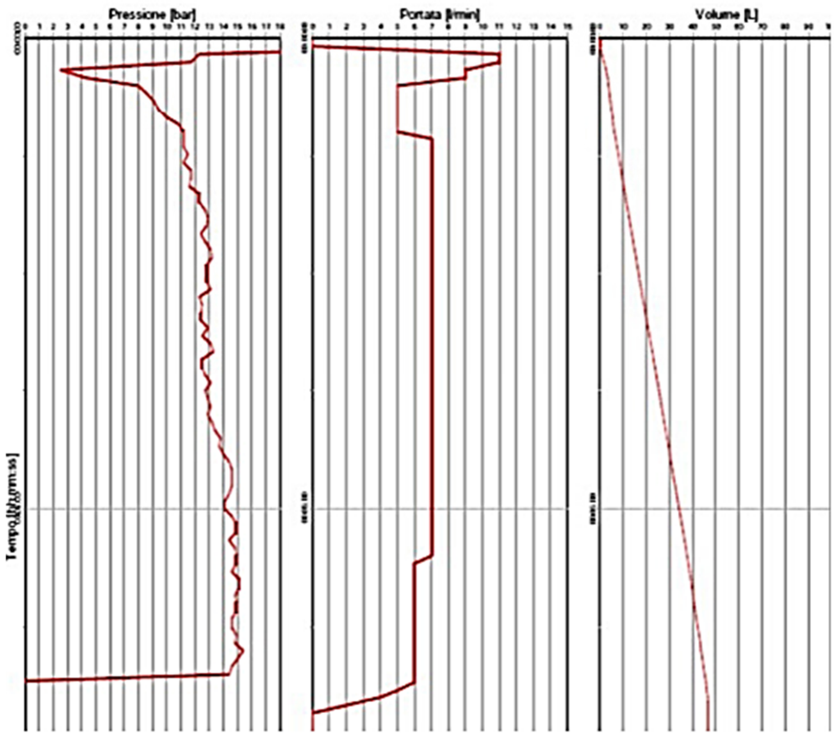


Figure 5: pressure, flow and volume values recorded over time during the injection of a valve tube (Pettinaroli et al, 2019)

The pressure and volume values recorded for each individual valve, of each manchettes tube, for each pass, are displayed graphically by means of a colour scale, to indirectly observe the overall progress of the injection operation and to identify valved tubes or levels where the maximum permissible pressure is reached.

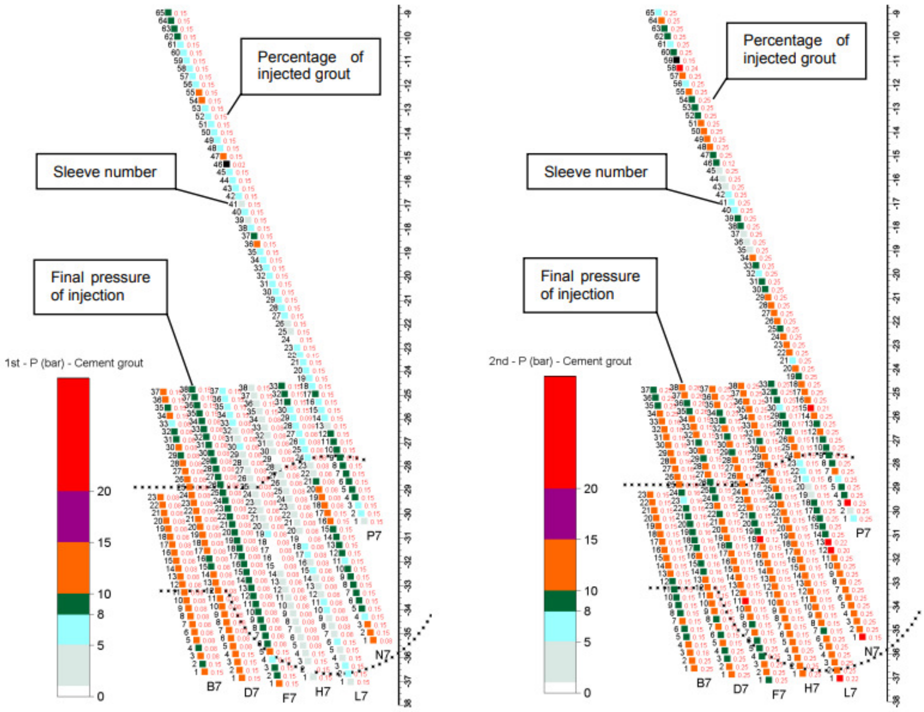


Figure 6: Grouting pressure-volume diagrams: 1st grouting stage on the left and 2nd on the right

2.3 Conceptual design of a cylindrical injection apparatus

As is evident in the previous paragraph, the technique of permeation grouting is complex, and the success of the treatment can only be assessed in situ indirectly. Regarding the groutability of a soil by a given mixture, the standard test carried out in the laboratory is the column injection test.

This test, in accordance with ASTM D 4320, allows the injectability of a mixture within a soil column to be assessed and allows cylindrical specimens of treated soil to be obtained for mechanical testing. This test is a simplified version of soil injection, it does not consider the three-dimensionality of the injection and the displacement of the mixture front, which in column injection is one-dimensional, from the bottom to the top of the candle. Furthermore, in this test neither the manchettes nor the bentonite liner are present, the flow rates are much lower than the actual in situ flow rates, as is the maximum injection pressure.

With the aim of carrying out injection tests in the laboratory that are similar as possible to the tests carried out in situ, an apparatus was designed that considers all those elements that are not considered in column injections. In this way, the results obtained from the tests are better able to replicate the reality of soil injections.

The equipment designed and subsequently built to carry out 3D injections of the mixture in a soil sample is characterized by cylindrical geometry.

This shape is the simplest and most natural to be used in an apparatus that simulates permeation grouting using manchette tubes. The consolidating mixture comes out at 360 °, both above and below the valves on the pipes, and is distributed radially in the ground forming an approximately spherical bulb (Kim, J. S et al., 2009).

Figure 7: functioning of the TAM (left), treated soil bulb Kim, J. S et al., 2009 (right)

The machine was conceived as a cylinder inside which the sleeve tube is placed, centered on the axis of the cylinder.

In this apparatus, the casting of the bentonite liner for 3D injections is envisaged, and this represents an important innovation compared to the other 3D injection tests shown in the first chapter.

The sheath is in fact present around the manchettes during in-situ injections; during the injection phase of the consolidating mixtures, the pressurised mixture breaks the sheath and flows out of it radially.

The function of the liner is twofold: one function is to support the hole so that it does not collapse due to the horizontal stresses present in the ground, the liner exerts pressure on the edges of the hole which is a function of its density and depth.

Another function of the sheath is to prevent the mixture, which escapes from the valve, from flowing back down the manchettes, preventing it from becoming a preferential flow path. This is made possible by the fact that an interface is formed between the conduit and the soil, and this interface is rough, so that the mixture escaping from the conduit does not find a preferential flow path and is more evenly distributed within the soil volume.

The cylindrical apparatus is divided into three main parts: the lower part, the central part consisting of the cylindrical soil sample container and the upper part, these parts are described below.

2.3.1 Lower part

It consists of a 5 mm thick circular iron bottom plate, a series of iron beams that act as structural reinforcement, significantly reducing the deformability of the circular bottom, and supports that raise the plate to a height of 40 cm from the floor.

On the bottom there are holes that allow for the drainage of water and/or mixture and ten other holes that allow for the attachment of the central part to the lower part using a bolt - washer - nut system.

2.3.2 Central cylindrical container

The soil sample container is cylindrical in shape and designed in such a way that it is easy and quick to close and open this part.

After accurate market research, it was decided to use a plastic concrete column formwork as the cylindrical part.

This instrument consists of two semi-cylindrical parts that are closed and opened quickly using handles, making both the assembly phase and the opening, and unpacking of the treated sample simple.

The weight of the single semi-cylinder is 3.75 kg, which makes it easy to move and lift this part of the apparatus.

The internal volume of the two moulds, which are joined together, is 230 litres, the diameter is 700 mm, and the height is 600 mm, the soil sample is contained here, and the height is 350 mm. Along the inner wall of the cylindrical formwork, a geo - net, coupled with geotextile, is placed to act as a drain.

2.3.2.1 Drain

Inside the cylindrical equipment, and the wedge-shaped prototypes, there is a drain in contact with the walls, when the mixture reaches the drain, it precipitates by gravity and comes out of the equipment through the holes in the bottom of the same.

In the tests carried out using the cylindrical injection equipment, the drain consists of a geonet, coupled to a geotextile.

"They are composed of a draining network with three orders of superimposed and crossed wires: the internal wires of greater thickness ensure a high capacity and resistance to compression of the structure, while the transversal wires prevent the intrusion of the geotextile to guarantee the flow of project. Tendrain triplane geocomposites maintain constant hydraulic capacity over time as they are not subject to compression creep." (Tenax website)

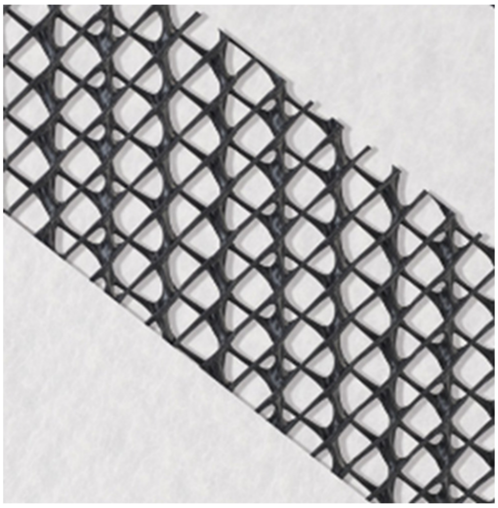


Figure 8: photograph of Tendrain (Tenax website)

2.3.3 Upper part

The upper part of the apparatus, which serves as the lid, is composed of a metal disc with a circular opening in the centre that allows the hole support tube and manchettes to be pulled out. The lid is reinforced by means of a system of square profile beams welded onto the circular plate.

Welded to the reinforcement beams are rectangular beams that rise from the lid, and above which are welded two rectangular beams parallel to the bottom that act as a frame and, using threaded rods, allow the soil sample to be confined by giving it a vertical load.

2.4 Numerical analysis for parts sizing

As regards the sizing of the lower and upper metal parts of the machinery, models of the 1D and 3D structure were made, with the Midas GTS NX software, to verify stresses and deformations acting on the structure.

GTS NX is a 3D finite element modeling (FEM) software, which is based on the equations that define the geotechnical problem: equilibrium, compatibility, constitutive model, continuity (fluid - soil). The continuous medium is discretized, boundary conditions and initial conditions are imposed, and finally the equations are integrated.

The software allows: sophisticated 3D analysis for problems related to the soil-structure interaction, excavations, slope stability, dynamic and seismic analyzes, transient and stationary filtration motions, consolidations, settlements (GTS NX site).
With the software, the geometry of the apparatus is created, the characteristics of the constituent materials are defined, the mesh is created, and the loads on the structure and constraints are applied. The calculation of acting stresses and deformations makes it possible to design the structure of the apparatus by minimizing the deformations acting on its constituent parts. As a result of these calculations, the bottom and lid were made of 5 mm thick steel, the box-profile beams used to stiffen the bottom and lid are 50x50x4 mm square cross-section, and the box-profile beams that serve as frames and are placed under the bottom and above the lid are 100x50x4 mm rectangular cross-section.

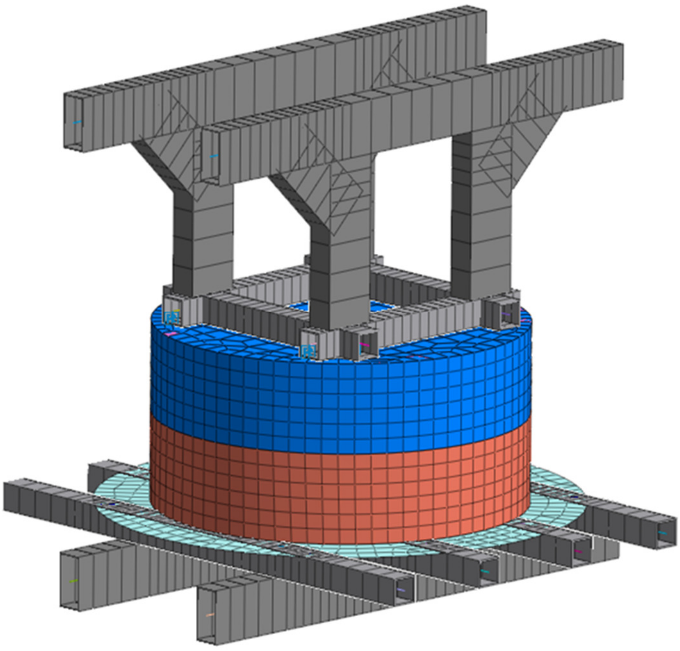


Figure 9: geometric model with activated geometric properties of beams modeled as 1D elements.

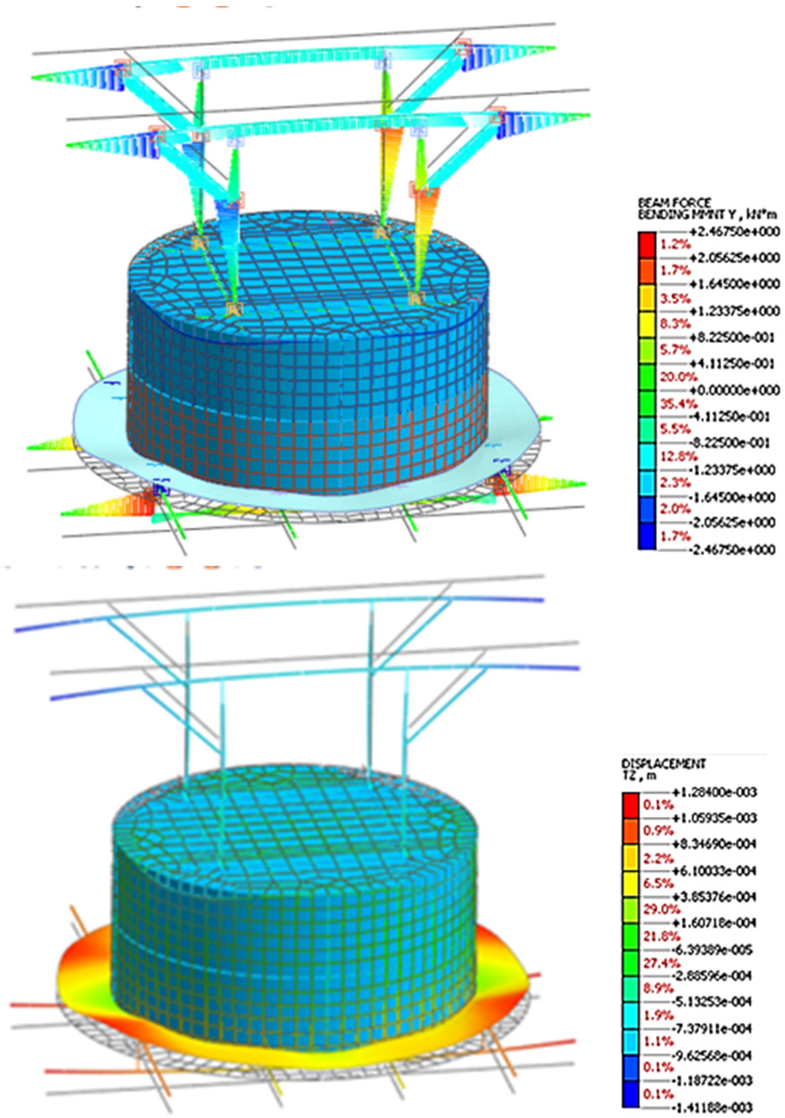


Figure 10: geometric model with beams modeled as 1D elements (on the left the forces acting by applying 14 kN on the frame, on the right the corresponding deformations)

2.5 In situ equipment

A further innovation is the use of equipment used in situ, so that the injection is as similar as possible to a permeation grouting injection performed on site, particularly in terms of pressures and flow rates.

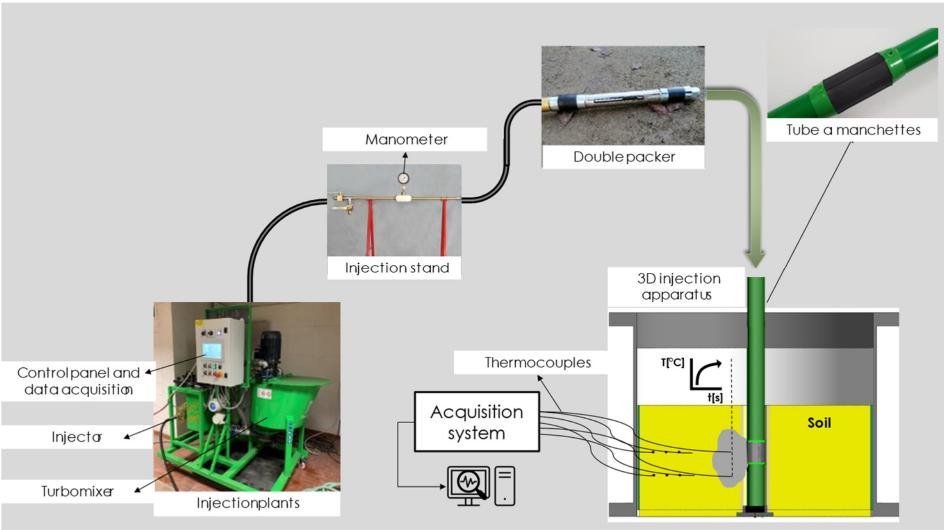


Figure 11: conceptual scheme of a 3D injection

The following sections describe the instrumentation used to carry out injections within the cylindrical apparatus.

2.5.1 Injection plant: injector and turbo mixer

For the preparation of the mixtures, the MDPT150-DEOL3 system was used, consisting of a turbo mixer and injector. This system is equipped with a screen through which it is possible to set the injection parameters for each valve of each valve tube and read the injected volume, pressure and flow rate values of the mixture in real time during injection.

The working parameters can be set manually using the touchscreen or remotely, by connecting the machine to the network and connecting to it via a PC.

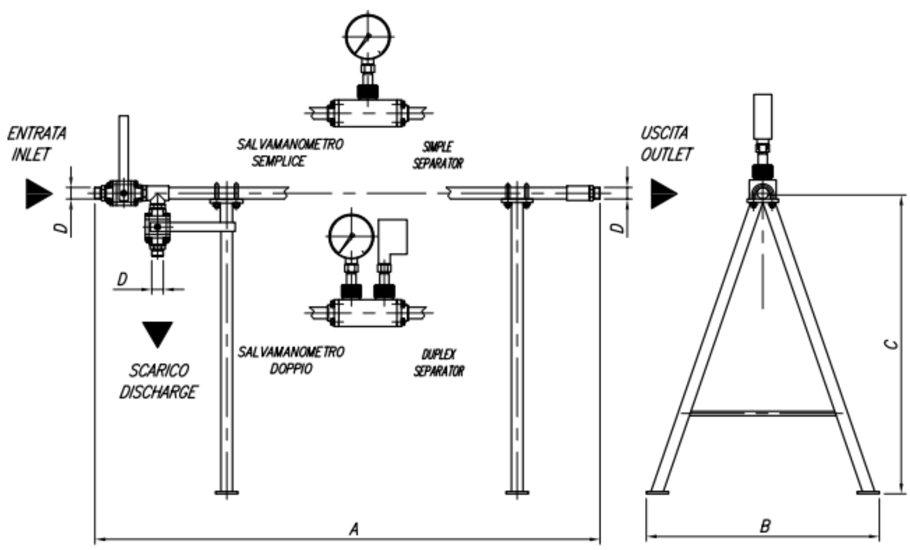
The plant has compact dimensions (192x106x195) and is mounted on wheels, so that it can be transported inside and outside the university laboratories.

Figure 12: MDPT150-DEOL3 compact injector and turbo mixer

2.5.2 Injection stand

An injection stand is mounted in series on the line that carries the mixture from the injector to the packer.

"The injection support is a complete equipment of ball valves, save pressure gauge and connections for flexible pipes with threated swivel nut. The stand is available in two version: with connections ¾'' G and 1'' G, as desired, with the simple separator for pressure gauge to have only a visual reading of the pressure, or with duplex separator pressure gauge, for the chance to mount a pressure transducer for the detection and recording of injection parameter." (Online catalogue Ceribelli e Bianchi).



INGOMBRI E DATI TECNICI / DIMENSIONS AND TECHNICAL DATA

Diametro nominale Nominal diameter	Pressione max. di esercizio Max. working pressure	A	B	C	D	Codice Con salvamanometro semplice	Code With simple separator	Codice Con salvamanometro doppio	Code With duplex separator
DN 20	120 bar	1200	530	700	3/4" Gas	CIS200100			
DN 25	120 bar	1200	530	700	1" Gas	CIS250100			
DN 20	120 bar	1200	530	700	3/4" Gas			CID200200	
DN 25	120 bar	1200	530	700	1" Gas			CID250200	

Figure 13: injection stand datasheet and dimension.

2.5.3 Tube a manchettes

Durvinil valve tubes, with a nominal diameter of 1 ", 40 mm of internal diameter and 48 mm of external diameter, and external valves with sealing ring were used as valve tubes.

"The standard DURVINIL® valved tubes are used for the injections of cement and chemical mixtures of the soils. In the valve sections, every 33-50-100 cm, there are non-return valves that allow the passage of the cement mixture only in the direction of the ground, preventing the backflow of the fluid inside the pipe.

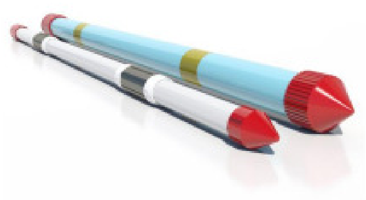
DUR-O-RING hand valves allow:

- *selective injection: it is possible to choose which valve to inject and monitor the value of the pressure and volumes injected over time, for example through a data logger.*
- *to repeat the injection over time. The DUR-O-RING valves guarantee a perfect closure after each injection cycle allowing their use in the future.*
- *to vary the type of mixture injected (standard cements, microfine, silicates ...)*

The tubes with valves for injections of cement mixtures (rods with manchette), are available from 1 " to 2 " 1/2 in diameter and in bars up to 6 meters that can be joined through threaded sleeves.

Depending on the use, the injection valves can be of the external type with ABS protection rings or in the thickness of the tube. " (Sireg Geotech website).

Durvinil® sleeved grouting pipes (TAM)



Durvinil® sleeved TAM pipe with smooth internal surface and ports, covered by rubber sleeves (DUR-O-RING). The pipe is threaded at both ends and can be joined by means of external ABS connection couplings in order to reach the desired lengths.

DURVINIL® SLEEVED GROUTING PIPES – STANDARD TYPE

The **DURVINIL® sleeved TAM pipe** is manufactured with rigid PVC. It has a smooth internal surface and spaced perforations (standard sleeve spacing is 330mm or 500mm). These perforations are covered by "flush" or "external" **DUR-O-RING®** rubber sleeves, also called "manchette," which act as non-return valves. The pipes are delivered in standard lengths of 3 or 5 meters. Both extremities are threaded and by means of external ABS connection couplings, they can be connected to each other to reach the total length required.

DURVINIL® STANDARD TYPES			
Nominal diameter	Inner/outer diameter	Sleeve type	Packer
1 " 1/8	28/38 mm	External	SIREG Rigid 28
1 " 1/2	40/48 mm	External	SIREG Hydraulic 30
	40/50 mm	Flush	SIREG Hydraulic 30
2"	50/60 mm	External	SIREG Hydraulic 42
2"	50/60 mm	Flush	SIREG Hydraulic 42

DURVINIL® REINFORCED SERIES sleeved grouting pipes are manufactured with a special shock resistant PVC with extra wall thickness and sealing gasket. These pipes have higher bursting pressure and are recommended to be used with preventer or HDD applications.

DURVINIL® REINFORCED SERIES			
Nominal diameter	Inner/outer diameter	Sleeve type	Packer
2"	45/60 mm	Flush/External	SIREG Hydraulic 30
2"	40/60 mm	Flus/External	SIREG Hydraulic 30
2" 1/2	55/75 mm	Flush	SIREG Hydraulic 42

In case of specific needs, DURVINIL® grouting pipes can be ordered with additional sleeves, reinforced Alu-Coupling and in custom length.

Figure 14: datasheet Durvinil sleeved pipe (Product catalog, Sireg Geotech site)

2.5.4 Double packer

A double hydraulic packer was used to carry out the injection into the valve, this tool allows you to isolate each single valve to be injected. It works with oil, a manual pump allows you to give pressure in an oil circuit to compress the rubber seals, which, when compressed, expand in a radial direction.

The dual packer allows the volume around each valve to be isolated, so that the mixture is injected into the soil in a controlled manner, valve by valve, having control over the volume of mixture flowing out of each individual valve.

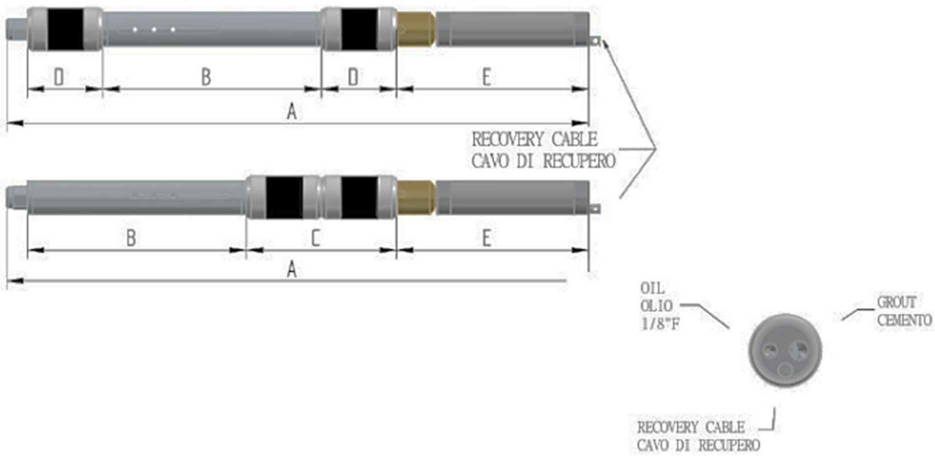


Figure 15: schematic representation of double packer

2.6 Sensors e acquisition system

2.6.1 Thermocouples

Thermocouples are temperature sensors that exploit the Seebeck effect, the potential difference measured at one end of a pair of cables (cold junction) is proportional to the temperature difference between the cold junction and the other end of the pair of cables (hot junction).

During the injection tests type K thermocouple wires are placed inside the soil sample, with a known arrangement. Since the soil and the consolidating mixtures have significantly different temperatures, thermocouples are used as indicators of the passage or failure of the mixture in the point where the hot junction is placed.

The TEX / TEX-30-KK thermocouples cables are from Chromel-Alumel, the insulation in Teflon, dimensions 1.2 x 1.8 mm.

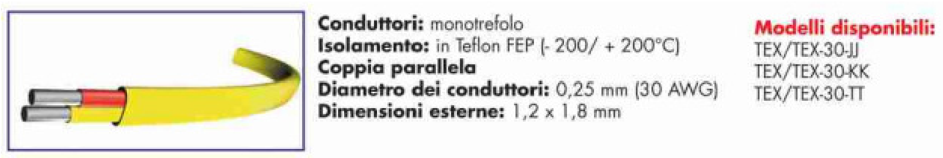


Figure 16: datasheet of TEX/TEX-30-KK thermocouples (Tersid website)

2.6.2 Datascan 7000 series

Datascan 7220 is a 16 analog channels datalogger used to acquire data from thermocouples, this instrument is managed by software installed on a PC.

"The measurement processor performs the measurement and control of the Datascan system. Measurement is carried out by a powerful Analog to Digital converter, which can be programmed to provide either 16 or 14 bits of resolution and is sensitive to 0.625µV". A typical measurement speed is 1 Hz. (Datasheet of Datascan 7000).

The connection of the data logger to the PC takes place via the serial port 232.

Before starting the acquisition of signals from individual sensors, it is possible to set each individual channel by assigning it name, unit of measurement, and calibration law.

The data is saved in a text file, which can be opened and edited in Excel, allowing the processing of the recorded data.

Figure 17: photograph of Datascan 7220

2.6.3 Bleb

An innovative acquisition system was used to acquire the signal coming from the sensors, based on Bluetooth Low Energy communication technology.

The acquisition system involves the combined use of different Bricks. The solution chosen involves the use of the package consisting of a power brick, a Bluetooth communication brick, a voltage acquisition brick (to which the thermocouple is connected) and a connection brick.

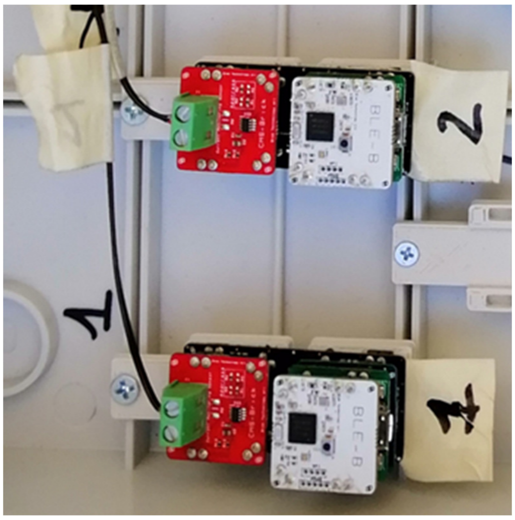


Figure 18: two Bleb system acquisition for thermocouples

An App, specially created in the App Inventor environment, allows you to acquire and save data on a smartphone device.

The creation of apps in the App Inventor environment is simplified; in fact, one does not have to write the entire code, but there are logical blocks to associate with each other.

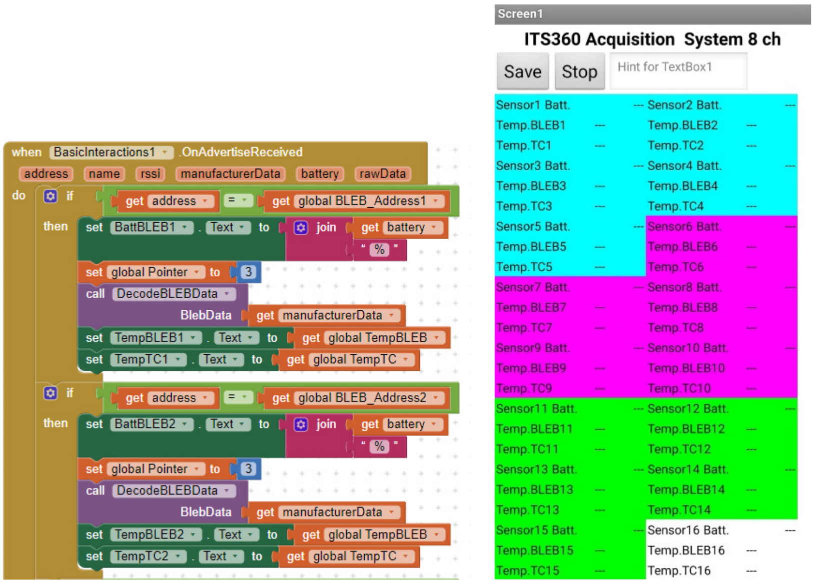


Figure 19: a part of the code, on which is based the App (on the left), a screenshot of the App installed on a smartphone (on the right)

This acquisition system is particularly advantageous whenever you operate in sites where the power line is not available, or it is difficult to access, thanks to the power supply with rechargeable lithium-ion batteries.

References Chapter 2

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Chapter 3

Construction and assembly of the apparatus

3.1 Introduction

The following paragraphs present the apparatus parts, materials and size, realized on the basis of the conceptual design set out in the previous chapter and on the strength and deformability calculations of the constituent parts of the apparatus.

After describing the constituent parts, the assembly of the structure and preparation of the sample, which must be carried out before the injection tests can be performed, are described.

3.2 Construction

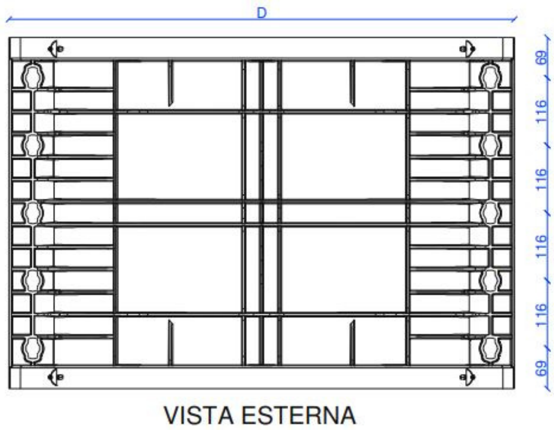
3.2.1 Cylindrical formwork

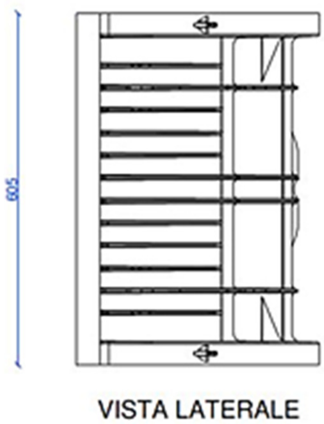
During the design and sizing phase of the device, the diameter was set at 700 mm. The maximum penetration radius of the mixture is therefore 350 mm.

The volume of soil used during a test, considering diameter 700 mm and height 330 mm, is about 130 l, corresponding to more than 200 kg of dry material, larger dimensions of the soil sample would make it difficult to manage and extremely expensive to carry out tests.

The cylindrical GEOTUB formwork was chosen, the object is made of ABS, has a weight of 7.54 kg, an inner diameter of 700 mm, a height of 605 mm and a thickness of 82 mm (technical datasheet of GEOTUB).

Formwork GEOTUB is equipped with handles for quick opening and closing.





GEOTUB	D	R
Ø 70	864 mm	350 mm
Ø 80	964 mm	400 mm
Ø 90	1.064 mm	450 mm
Ø 100	1.164 mm	500 mm

Figure 1: lateral view of formwork and its dimensions (Technical datasheet of GEOTUB)

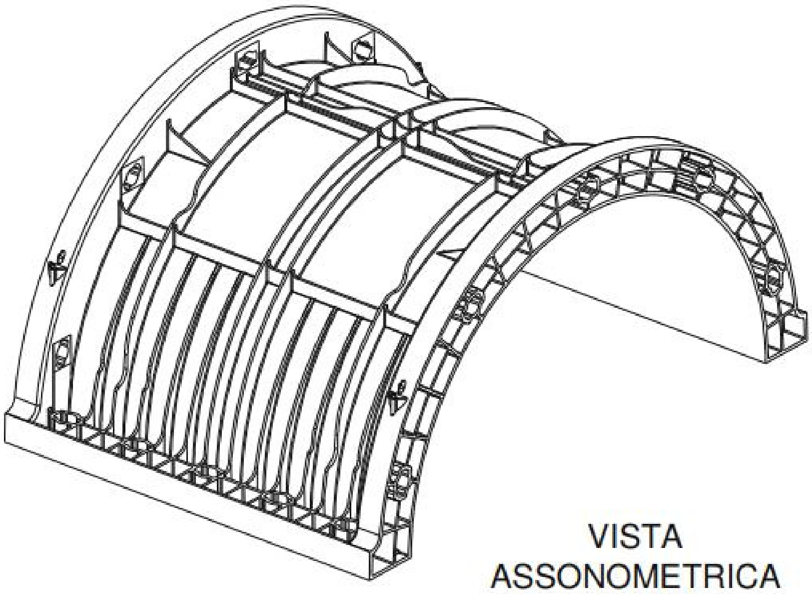


Figure 2: axonometric view of formwork (Technical datasheet of GEOTUB)

Figure 3: formwork photography (site of Geoplast)

3.2.2 Apparatus lower part

The lower part was manufactured by a workshop that performs metalwork. It consists of a circular iron bottom with a diameter of 880 mm and a thickness of 5 mm. Below the bottom are welded four 50x50x4 mm square-section beams with the function of stiffening the structure.

Below these beams are welded, in a direction orthogonal to the square-section beams, two rectangular-section 100x50x4 mm beams, these beams have holes at their ends through which threaded rods used to give the soil a surface load pass.

Finally, under these rectangular-section beams, four 50x50x4 square-section beams are welded in a vertical position. These beams have a length of 310 mm, and their function is to provide support for the substructure and to raise it above the floor.

On the circular plate there are sixteen holes, ten holes arranged at 36° from each other along the circumference serve to pass the bolts that secure the formwork to the underside. The remaining six holes are made to allow drainage of water and/or mixture during the injection phase.

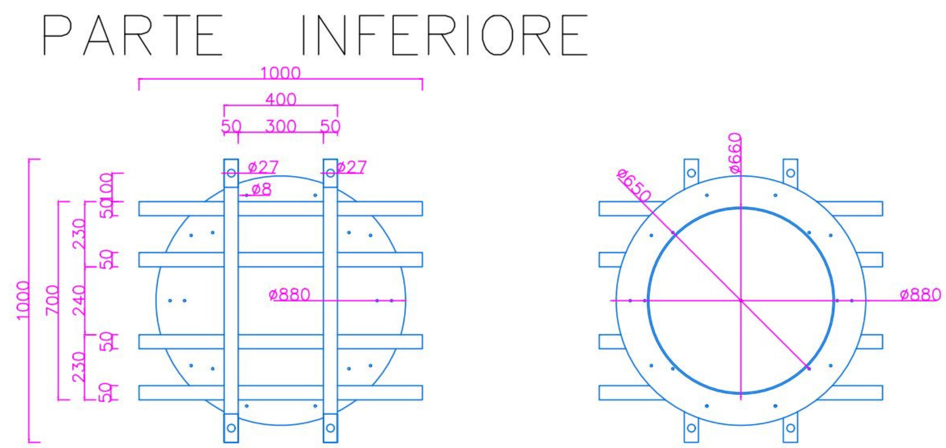


Figure 4: bottom and top views of lower part of the apparatus, the measurements are expressed in mm.

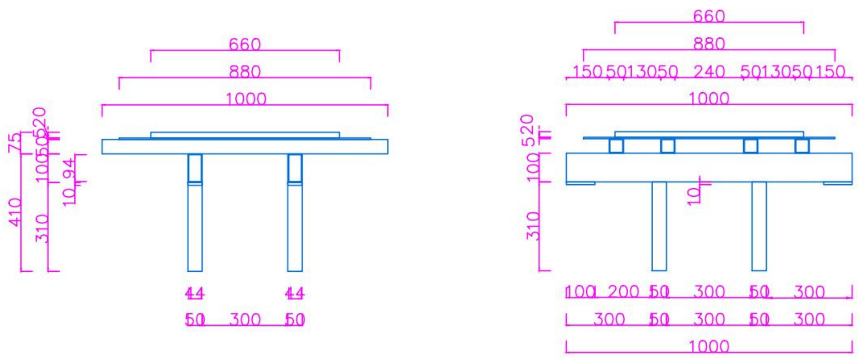


Figure 5: lateral view of the lower part of apparatus, the measurements are expressed in mm.

3.2.3 Upper part of the apparatus

The upper part, as well as the lower part, was made by a workshop that carries out metalwork. It consists of a circular iron cover with a diameter of 680 mm and a thickness of 5 mm. In the center of the cover there is a 120 mm circular hole, through which the hole support tube can be pulled out after the sheath has been cast. On the cover, around the central hole, six M8 threaded rods are welded, which are used for the attachment of a flange that increases the volume, and thus the load, of sheathing.

Above the cover, four 50x50x4 mm square-section beams are welded to stiffen the cover. Above these are welded, in a vertical position, four beams with a rectangular section 100x50x4, to which are welded two beams of the same size drilled at the ends to allow the passage of threaded rods.

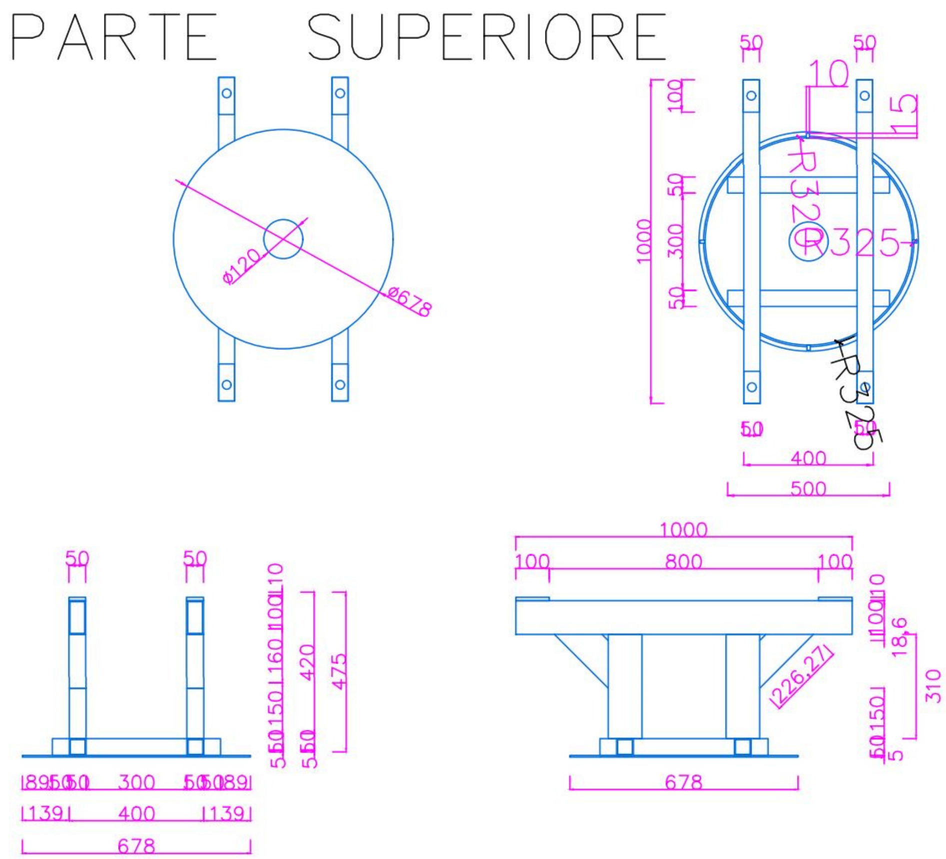


Figure 6: upper part of the apparatus, bottom, top and lateral views, the measurements are expressed in mm.

3.3 Assembly stages

In this section, the assembly steps for the 3D injection apparatus are listed and described, and assembly pictures are shown.

Assembly begins by fixing the cylindrical formwork to the bottom plate using ten M8 threaded bolts and nuts. Inside the formwork the thermocouples, manchettes tube and hole support tube are inserted.

After securing the formwork, the geo-network with drainage function is positioned.

Figure 7: assembly stages

The next stage is the filling with the soil to be treated; the sample must have a minimum height of 340 mm.

The soil inside the apparatus is laid down in layers: the contents of two sandbags (50 kg) are poured into the cylinder, the material is compacted using the tamping technique until the desired porosity value is obtained.

This technique, described in many works such as that of Raghunandan et al. (2012), consists of impacting a cylindrical mass on the surface of the soil sample from a fixed height, consolidating the soil. In this way it is possible to obtain the laboratory reconstituted soil samples with control over relative density and porosity, tamping can be done on both dry and wet soil.

When the thickness of the soil reaches the predetermined height for it to reach the required relative density value, the material contained in two more sandbags is poured into the apparatus and compacted as before; the operation can be said to be complete when the height of the soil sample is at least 34 cm.

After filling the apparatus with the soil, the lid is placed on top of the soil and the vertical load is transferred via the threaded bars.

Figure 8: 3D injection apparatus with the upper part

After positioning and securing the cover with threaded rods, the cement - bentonite mixture is prepared and cast to support the borehole. The casing pipe is slowly lifted, and sheath is added during the extraction phase until the pipe is completely pulled out. At this point, the flange is attached to the lid and further sheathing is cast until the flange volume is filled.

The sheath is cured in such a way that it sets and becomes solid, but at the same time still retains a good plasticity, as is the construction practice, described in many articles such as: Balossi Restelli A. (1968), Granata R. et al. (2012) and Di Salvo et Granata (2022). During the setting and curing phase of the bentonite sheath, the sample is not moved or disturbed.

After the curing time of the sheath has elapsed, it’s possible to proceed with the injection test.

Figure 9: assembly of the superior flange

Figure 10: cylindrical apparatus and injection plant

References Chapter 3

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Chapter 4

Laboratory test for choose granular material

4.1 Introduction

Before carrying out injection tests using the cylindrical apparatus (3D injection test), it is necessary to carry out column injection tests (1D injection tests) to determine which granular materials are injectable and which are not by the consolidating mixtures to be used, which will be described later in this chapter.

On the treated and consolidated soil samples obtained following the injection tests, mechanical characterisation tests are carried out.

4.2 Column injection test

The column injection test is a standard type of test to be performed in the laboratory. The structure of the column and the injection system of the mixture are described in many works in the literature and are fixed in the ASTM D4320 and UNI EN 1771 2005 standards.

The test involves the use of a column consisting of a tube in transparent plastic material, at the ends of which there are centrally perforated plugs to allow the injection of the mixture, from the bottom upwards and the drainage of water and air present in the soil before treatment. Inside the column there is a barrier consisting of a metal mesh, above the base cap and under the top cap, and a drain in coarse material (gravel), between the metal barriers and the soil contained in the column.

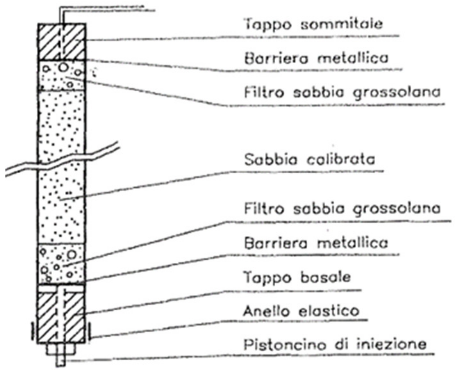


Figure 1: schematic section of a column

To carry out the injection, a pressurized barrel is used, equipped with a pressure gauge and pressure regulator.

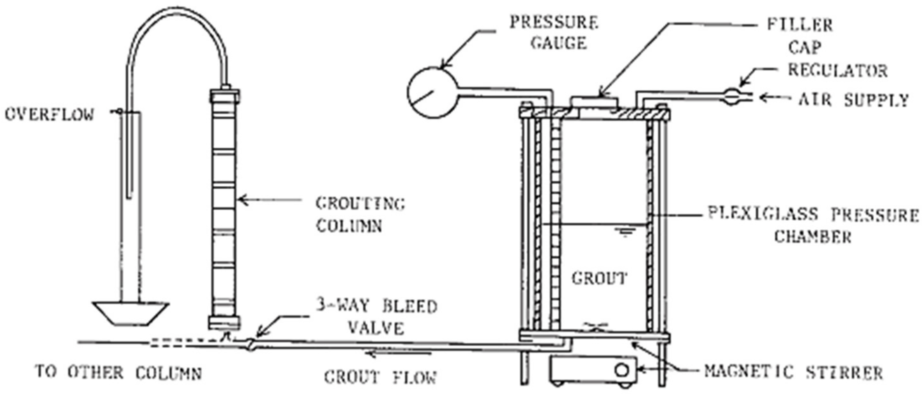


Figure 2: equipment for column injection in according to ASTM D4320

The injection of different mixtures, in soils with different granulometric characteristics, to evaluate groutability, soil resistance and the reduction of permeability following treatment, are described by several authors, listed below.

Krizek, R. J., & Perez, T. (1985) present the injection of different chemical mixture, silicate, and acrylate, in soil characterized by different grain size distribution.

Zebovitz, S., Krizek, R. J., & Atmatzidis, D. K. (1989) evaluate the injectability of microfine cement MC-500 mixture in sands with different grain size distribution, also a correlation between permeability of grouted soil and the unconfined compressive strength of this soil is proposed.

Anagnostopoulos, C. A., Chrysanidis, T., & Anagnostopoulou, M. (2020) performed column injections to obtain grouted soil to be subjected to UU triaxial test, to evaluate how the use of different superplasticizers and the different w / c ratio affects the mechanical strength of the material.

Santagata, M. C., & Santagata, E. (2003) carried out a series of experimental column injection tests to evaluate the penetration height achieved by mixtures with different rheological characteristics.

The authors cited above are only a small part of those who used the column injection test to evaluate the injectability of a given mixture in a given medium and to mechanically characterize the treated soil.

4.3 Equipment

The column injection tests, carried out in the laboratories of the University of Milan-Bicocca, refer to the ASTM D4320 standard and the numerous injection tests found in the literature.

The main elements are briefly described below.

4.3.1 Plastic transparent material column

The transparent material tube, inside which the soil to be treated is contained, is made from a transparent PVC sheet.

The sheet is rolled up on a rigid support with a diameter of 38 mm and fixed on a flap with a double-sided adhesive tape; two more turns are made with the PVC sheet to increase the stiffness of the pipe, then the second flap is fixed using a transparent tape.

Reinforcement hoops are made along the development of the column using a fiber-reinforced adhesive tape, and finally a strip of graph paper is applied along the tube to monitor the progress of the mixture during the injection phase.

Figure 3: an example of a column realized with transparent PVC.

4.3.2 Perforated caps

The caps used to close the candle at the top and bottom are made of plastic, in their center there is a hole of 8 mm in diameter that allows the passage of water during the saturation phase and of the mixture during the subsequent injection phase.

To ensure the hydraulic seal between the column and the cap and between the cap and the injection and drainage pipes, grooves are made on the cap, inside which sealing O-rings are housed.

There is sealing O-rings between the cap and the column and two O-rings inside the central hole to ensure sealing between the cap and the injection pipe, as shown below.

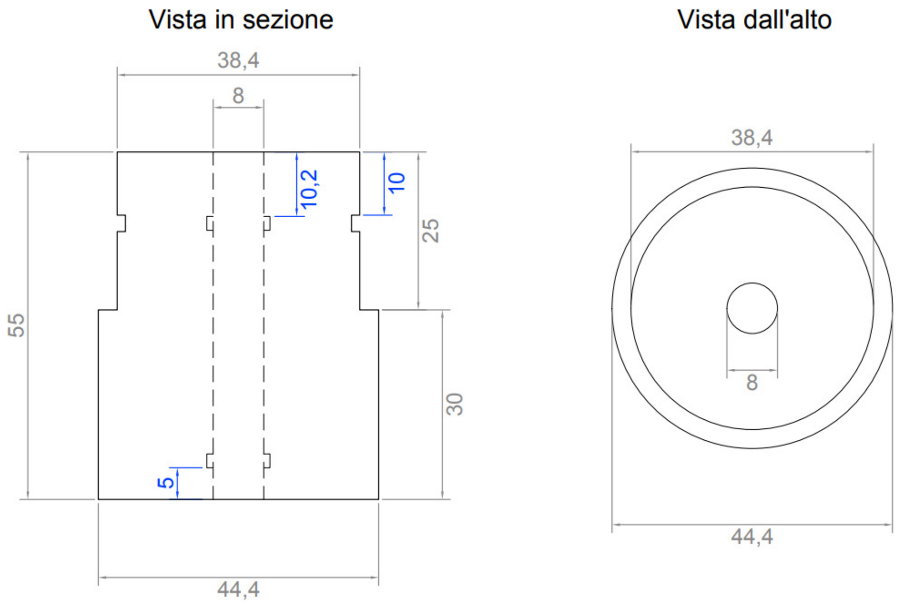


Figure 4: section and top view of the cap

On the top of the cap there are grooves arranged in a radial pattern that allow the mixture, which comes out of the cap, to flow uniformly inside the column.

Screw hose clamps are used to further secure the cap to the column.

4.3.3 Pressure barrel

The system that allows to inject is a container under pressure, consisting of a polycarbonate cylinder, closed at the top and bottom by two PVC caps.

Plastic seals are placed along the contact surfaces between the cylinder and the bases, the system is closed using threaded bars and bolts.

On the top cap there are three holes: the first constitutes the inlet of the pressurized air, the second the outlet for the mixture inside the container, the third is the vent of the compressed air once the injection has been completed for allow the opening of the container.

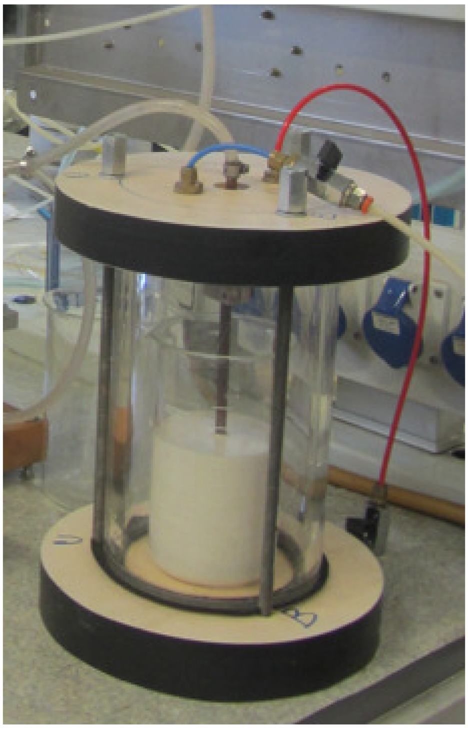


Figure 5: pressure barrel

The pressure is adjusted upstream of the injection barrel, using a manual pressure regulator equipped with a pressure gauge.

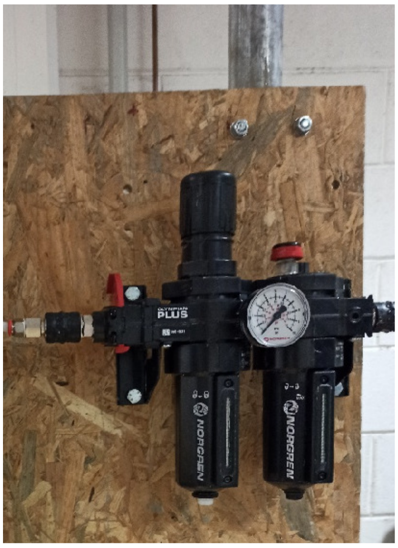


Figure 6: pressure regulator equipped with pressure gauge.

4.3.4 Fixing system

To ensure the verticality of the column during injection, a panel was created to which the columns are fixed by means of jaws. On the panel, made of wood, up to three columns can be housed at the same time.

The rear jaws are fixed to the panel, while the front part, which tightens around the column caps, can be quickly opened and closed with screws.

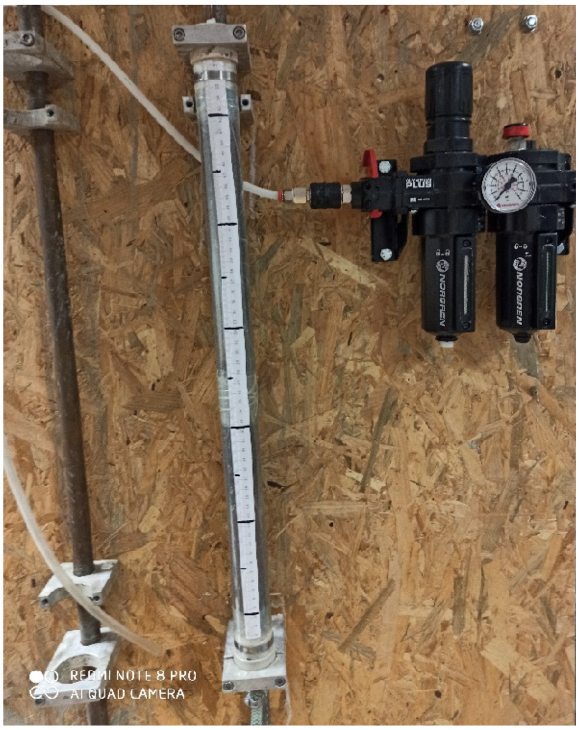


Figure 7: Column on his support

4.4 Experimental injection test

To evaluate the injectability of different soils and the mechanical characteristics developed by them following the consolidation treatment, column injection tests were carried out on soils with different grain size distribution. The media used, the consolidating mixtures and the results of the injection tests are described below.

4.4.1 Soils

In this section, the soils used in conducting the column injection tests are listed and described; the results of the column tests allow the selection of the soil to be used in the subsequent 3D injection tests.

Five distinct types of sand, in terms of origin, shape and particle size distribution, are used to perform the column injection tests. The different soils will be renamed below, for simplicity, Soil #1, Soil #2, Soil #3, Soil #4 and Soil #5.

The soils are characterized by their own particle size curve, obtained in accordance with ASTM D422. From the particle size curve, the characteristic diameters used in Burwell's formula to determine the groutability $\mathbf{D_{15}}$ and $\mathbf{D_{10}}$ were calculated, corresponding to the diameter through which 15 % and 10 % of the soil passes, respectively.

Soil #1 consists of an approximately monogranular quartz sand, with a rounded grain shape. Origin Zandobbio (BG), D15=1.25 mm, D10=1.1mm.

Soil #2 consists of an approximately monogranular siliceous gravel, with a slightly angular grain shape. Origin Costa de 'Nobili (PV), D15=1.25 mm, D10=1.17 mm.

Soil #3 is composed of material coming from the subsoil of Milan, sieved, and divided into granulometric classes and starting from these classes the soil has been reconstituted, D15=1.35 mm, D10=1.25 mm.

Soil #4 is composed of material coming from the subsoil of Milan, sieved, and divided into granulometric classes and starting from these classes the soil has been reconstituted, D15=0.34 mm, D10=0.19 mm.

Soil #5 consists of granular material with dimensions between 4 and 0 mm, commercially sold under the name of 4-0 screened sand. Origin Ticino River, D15=0.11 mm, D10=0.09 mm.

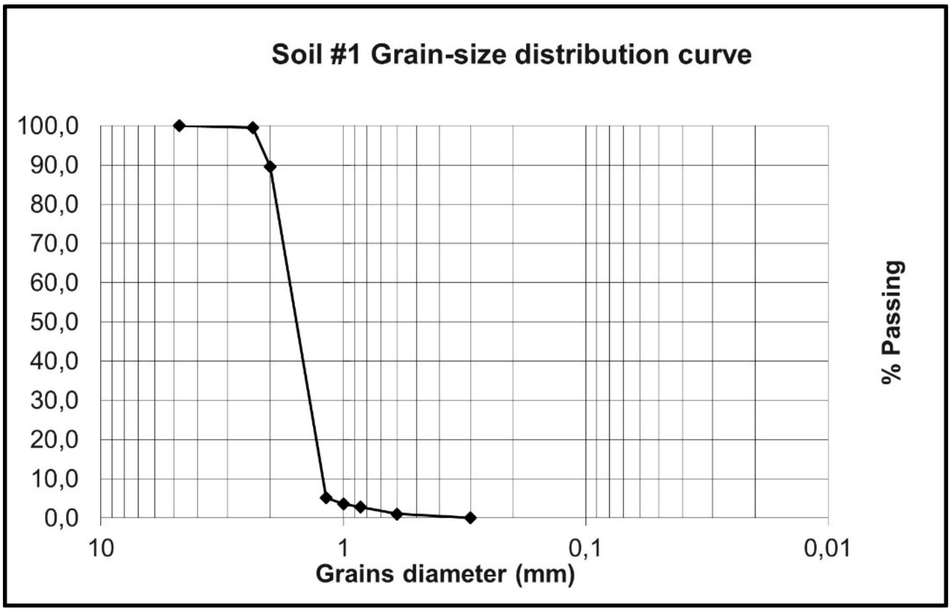


Figure 8: Grain size distribution of Soil#1

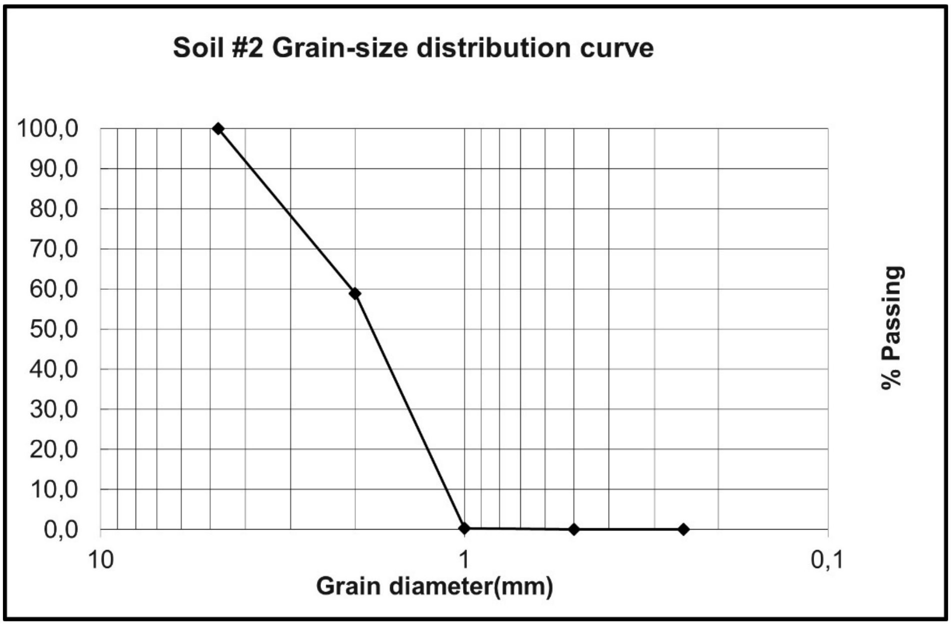


Figure 9: Grain size distribution of Soil #2

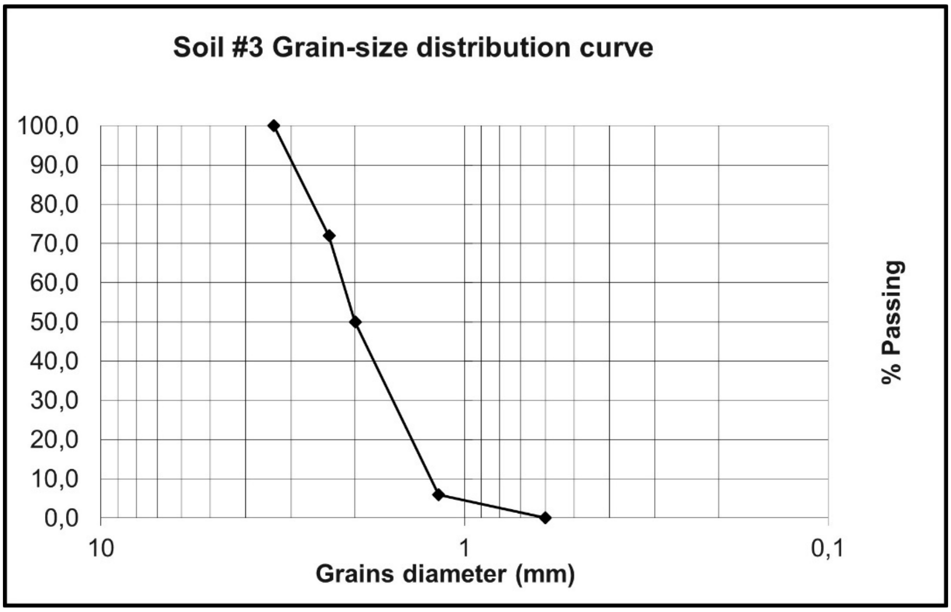


Figure 10: Grain size distribution of Soil #3 (coarse reconstructed soil)

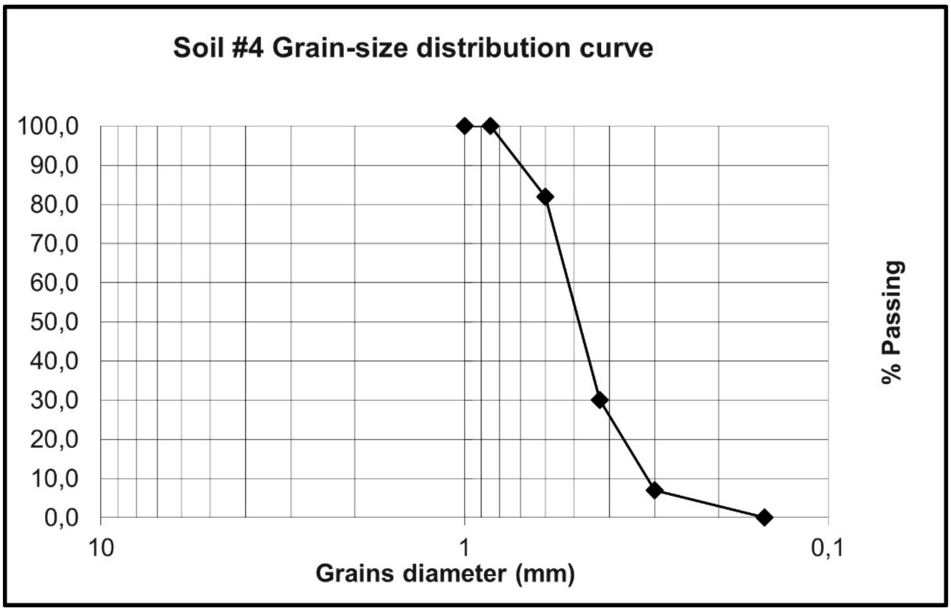


Figure 11: Grain size distribution of Soil #4 (fine reconstructed soil)

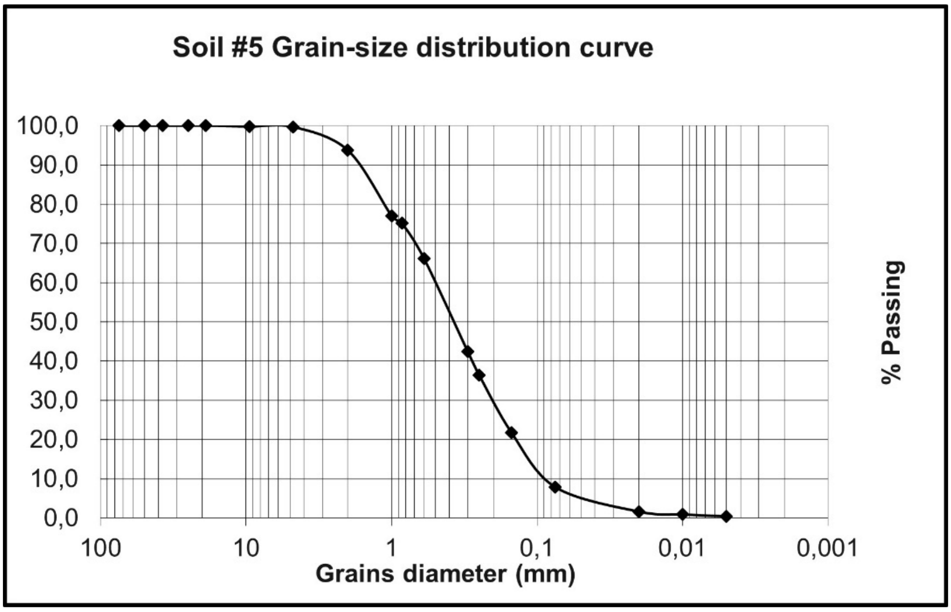


Figure 12: Grain size distribution of Soil #5

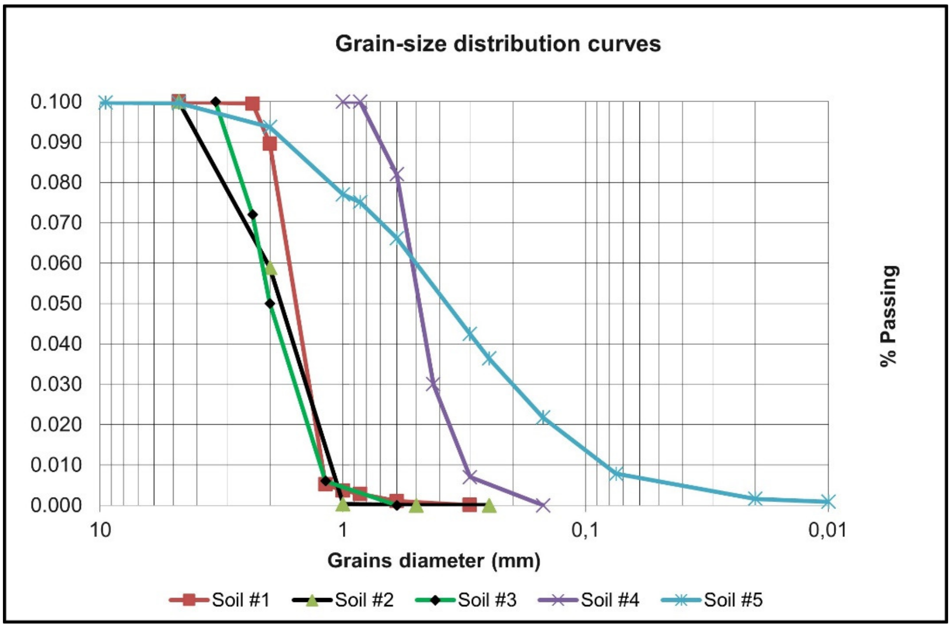


Figure 13: comparison between grain-size distribution curves of examined soils.

4.4.2 Mixtures

This section describes the three mixtures used during the column injection tests, hereafter named mixture #1, mixture #2 and mixture #3, the mix design and the rheological tests carried out on the mixtures after packaging.

Mixture #1 and mixture #2 are ternary mixtures of water cement and bentonite to which a fluidizing additive is added to reduce viscosity and promote injectability as described by Bremen (1997). Both are characterized by a w/c ratio of 2.5 by mass, a theoretical density of 1.25 kg/l, and viscosity values with Marsh Cone in the range of 35-36 s, values indicated as optimum for permeation grouting mixtures in sandy soils in the work of Pettinaroli et al (2019). What differs is the cement used.

The bleeding test, carried out on mixture #1 and mixture #2, showed a separation between the mixture and the water it contains of less than 1%. Since this value is less than 5%, the two mixtures can be considered stable, as reported in the works of Lombardi G. & Deere (1993) and Lombardi G. (1999).

Mixture #3 is a three-component silicate mixture: silica liquor, Carboslurry and reagent (NaOH) are dissolved in an aqueous solution. Depending on the different performance characteristics required, different mix designs can be obtained by balancing the chemical reactions between the three components and water.

The mix design and characteristics of the mixtures described above are shown below.

4.4.2.1 Mixture #1

T water	26 °C
Mixing mode	Turbo mixer
Mixing time	5 min

Components used	
Water	Acquedotto
Cement	52,5 UltraCem Italcementi
Bentonite	Sipag Bisalta - Y
Additive	Lamberti - Lamsperse BV

A1) Components quantity

Water	62,65 kg
Cement	25 kg
Bentonite	2,13 kg
Additive	0,22 kg

A2) Density (API RP 13B-1 2003)

Temperature	33 °C
Density	**1,231 kg/lt**

A3) Marsh Cone viscosity (API RP 13B-1 2003)

Durata	**35 sec**

A4) Initial viscosity with rotative viscosimeter Rheometer (API RP 13-1 2003)

Temperature	33 °C
L300	9 RPM
L600	15 RPM

Plastic viscosity VP	**6,0 cP**
Coesion YP	**1,4 Pa**
Apparent viscosity VA	**7,5 cP**

A6) Bleeding test (API RP 13B-1 2003)

1h	100 %
2h	100 %
3h	**100 %**

Figure 14:Mix design of mixture #1 and rheological characteristics

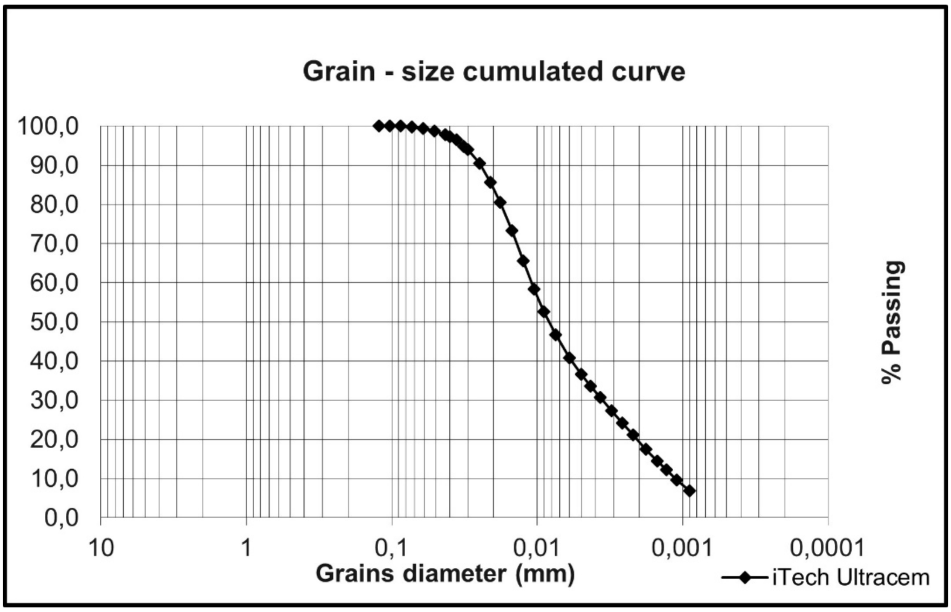


Figure 15: Grain size distribution of i-Tech Ultracem

4.4.2.2 Mixture #2

T water	12 °C
Mixing mode	Drill
Mixing time	12 min

Components used	
Water	Aqueduct
Cement	52,5 Holcim
Bentonite	Sipag Bisalta - Y
Additive	Lamberti - Lamsperse BV

A1) Component quantity

Water	3,48 kg
Cement	1,39 kg
Bentonite	0,118 kg
Additive	0,012 kg

A2) Density (API RP 13B-1 2003)

Temperature	17 °C
Density	**1,246 kg/lt**

A3) Marsh Cone viscosity (API RP 13B-1 2003)

Time	**35,5 sec**

A4) Initial viscosity with rotative viscosimeter Rheometer (API RP 13-1 2003)

Temperature	33 °C
L300	13,5 RPM
L600	21 RPM

Plastic viscosity VP	**7,5 cP**
Coesion YP	**2,9 Pa**
Apparent viscosity VA	**10,5 cP**

A6) Bleeding test (API RP 13B-1 2003)

1h	100,00 %
2h	99,8 %
3h	**99,7 %**

A7) Filterpress stability

Temperature (°C)	17

Time	Water (cc)
30''	5,45
1'	8,16
2'	12,25
4'	18,14
8'	26,61
15'	37,46
30'	54,53

CAKE

Cake height (mm)	5,2
Cake mass (gr)	44,35
Cake Note	
Filterpress water (cc)	242

NOTE

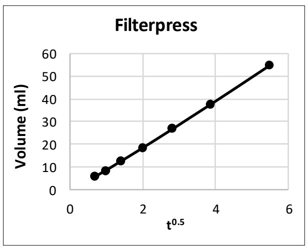


Figure 16: Mix design of mixture #2 and rheological characteristics

4.4.2.3 *Mixture #3*

T water	12 °C
Mixing mode	Mixer
Mixing time	5 min

Components used	
Water	Aqueduct
Silica liquor	PROCHIN
Carboslurry	PROCHIN
Reagent	PROCHIN

A1) Components quantity

Water	681 kg
Silica liquor	565,5 kg
Carboslurry	363 kg
Reagent	349,5 kg

A2) Density (API RP 13B-1 2003)

Temperature	23 °C
Density	**1,309 kg/lt**

A4) Viscosity with rotative viscosimeter Rheometer (API RP 13-1 2003)

Time [min]	T [°C]	L600 RPM	L300 RPM	AV [cP]	PV [cP]	YP [Pa]
0	23	12	6	6	6	0
5	23	12,5	6,5	6,25	6	0,24
10	22	13	6,5	6,5	6,5	0
15	22	13	7	6,5	6	0,48
20	22	13,5	7,5	6,75	6	0,72
25	22	13,5	7,5	6,75	6	0,72
30	22	14,5	7,5	7,25	7	0,24
35	22	15	8	7,5	7	0,48
40	22	16	9	8	7	0,96
45	22	18	10	9	8	0,96
50	22	20,5	11	10,25	9,5	0,72
55	22	25	14	12,5	11	1,44
60	22	34	18,5	17	15,5	1,44
65	21	46,5	26,5	23,25	20	3,12
70	21	62	38	31	24	6,72
75	21	83	51	41,5	32	9,12
80	21	96	59	48	37	10,56

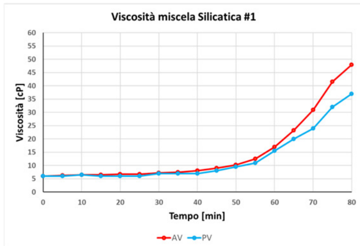


Figure 17: Mix design of three-component silicate mixture and rheological characteristics

4.4.3 Column injection test

After constructing the columns as reported in Section 4.2, eight injection tests were carried out, using different combinations of soil and mixture. This series of tests made it possible to assess the groutability or non-groutability of a soil by a given mixture and to measure the mechanical properties developed by the soil following the treatment.

The data thus obtained made it possible to select the most suitable material to be used in the 3D injection tests carried out with the experimental apparatus.

Listed below, for each column, are the soil used, the consolidating mixture injected, the outcome, positive or negative, of the injection and a table showing the density and porosity values of the soil within the column.

Column #1: soil #1 and mixture #1, injection completed.
Column #2: soil#5 and mixture #1, injection failed.
Column #3: soil #2 and mixture #1, injection completed.
Column #4: soil #2 and mixture #1, injection completed.
Column #5: soil #3 and mixture #2, injection completed.
Column #6: soil #3 and mixture #2, injection completed.
Column #7: soil #4 and mixture #3, injection completed.
Column #8: soil #4 and mixture #3, injection completed.

Column #1			Column #2		
Sand	Soil #1		Sand	Soil #5	
V_{sand}	0,567	[l]	V_{sand}	0,567	[l]
m_{sand}	0,925	[kg]	m_{sand}	1,092	[kg]
ρ_{dry}	1,631	[kg/l]	$\rho_{sand\ dry}$	1,926	[kg/l]
n	0,384	[-]	n	0,273	[-]
V_{voids}	0,218	[l]	V_{voids}	0,155	[l]
Injection of	Mixture #1		Injection of	Mixture #1	
Injection result	Completed		Injection result	Failed	

Figure 18: columns #1 and #2 characteristics and injection results

Column #3		
Sand	Soil #2	
V_{sand}	0,580	[l]
m_{sand}	0,961	[kg]
$\rho_{sand\ dry}$	1,657	[kg/l]
n	0,375	[-]
V_{voids}	0,217	[l]
Injection of	Mixture #1	
Injection result	Completed	

Column #4		
Sand	Soil #2	
V_{sand}	0,580	[l]
m_{sand}	0,968	[kg]
$\rho_{sand\ dry}$	1,669	[kg/l]
n	0,370	[-]
V_{voids}	0,215	[l]
Injection of	Mixture #1	
Injection result	Completed	

Figure 19: columns #3 and #4 characteristics and injection results

Column #5		
Sand	Soil #3	
V_{sand}	0,569	[l]
m_{sand}	1,013	[kg]
$\rho_{sand\ dry}$	1,779	[kg/l]
n	0,329	[-]
V_{voids}	0,187	[l]
Injection of	Mixture #2	
Injection result	Completed	

Column #6		
Sand	Soil #3	
V_{sand}	0,567	[l]
m_{sand}	1,044	[kg]
$\rho_{sand\ dry}$	1,841	[kg/l]
n	0,305	[-]
V_{voids}	0,173	[l]
Injection of	Mixture #2	
Injection result	Completed	

Figure 20: columns #5 and #6 characteristics and injection results

Column #7		
Sand	Soil #4	
V_{sand}	0,567	[l]
m_{sand}	0,947	[kg]
$\rho_{sand\ dry}$	1,670	[kg/l]
n	0,370	[-]
V_{voids}	0,210	[l]
Injection of	Mixture #3	
Injection result	Completed	

Column #8		
Sand	Soil #4	
V_{sand}	0,569	[l]
m_{sand}	0,948	[kg]
$\rho_{sand\ dry}$	1,664	[kg/l]
n	0,372	[-]
V_{voids}	0,212	[l]
Injection of	Mixture #3	
Injection result	Completed	

Figure 21: columns #7 and #8 characteristics and injection results

4.5 Mechanical tests on treated soils

The mechanical characterization of the treated and consolidated soil was carried out by carrying out mechanical tests on the samples obtained by injecting column as per the ASTM D4320 standard.

UCS tests, ASTM D2166 standard, were carried out on specimens obtained from all the injected columns.

As regards the material obtained by injecting columns #3 and #4, triaxial compression tests, ASTM D2850 standard, and Brazilian test indirect tensile tests, ASTM D3967 standard, were also carried out.

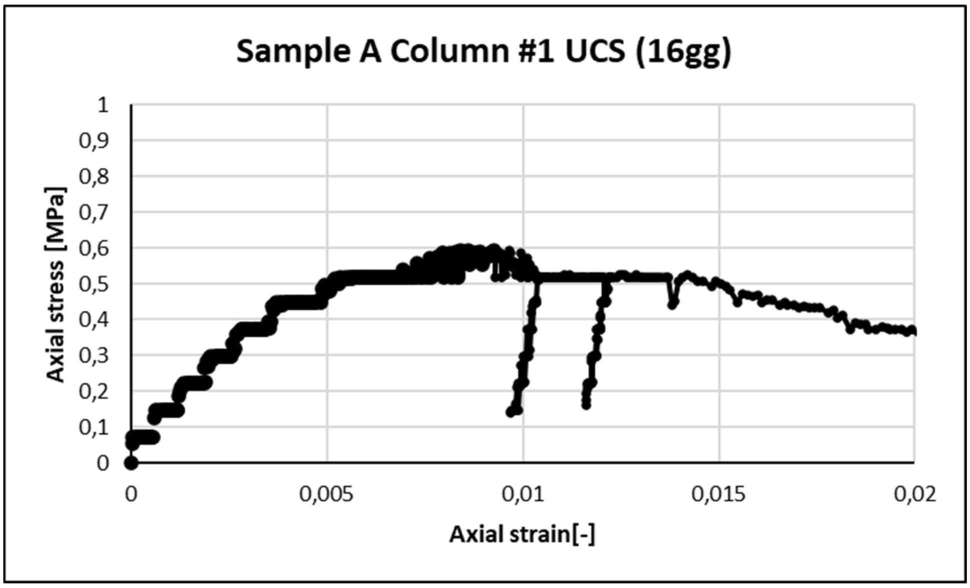
In the following paragraphs the tests are briefly described and the stress-strain graphs for each of the specimens are reported.

4.5.1 UCS

This test method concerns the determination of the unconfined compressive strength of the cohesive soil, in the unaltered, in a remodelled or reconstituted condition, using the deformation control during the application of the axial load.

This test method provides an approximate value of the strength of cohesive soils in terms of total stresses.

This test method is only applicable to cohesive materials such as clays or cemented soils in according to ASTM D2166 standard.



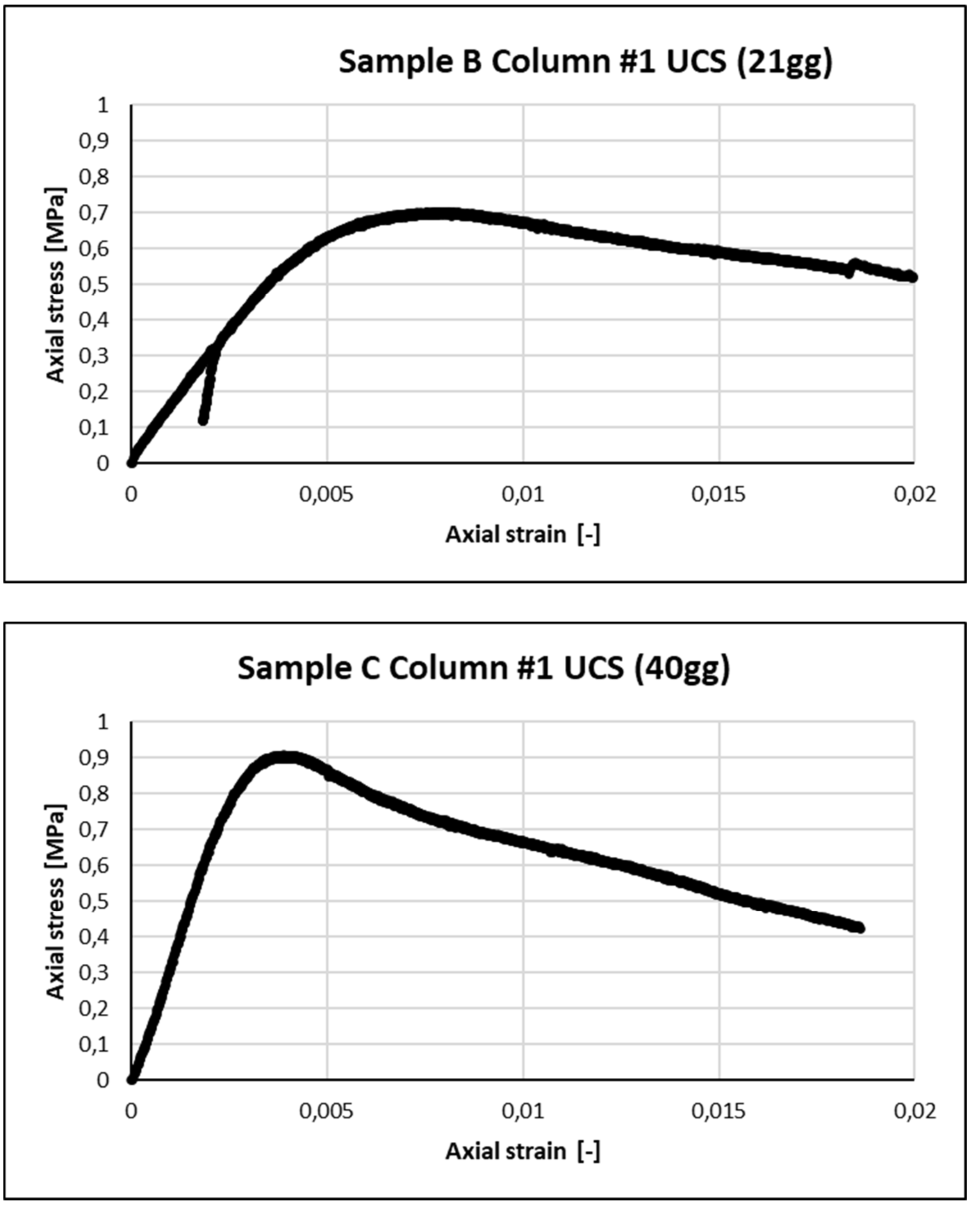
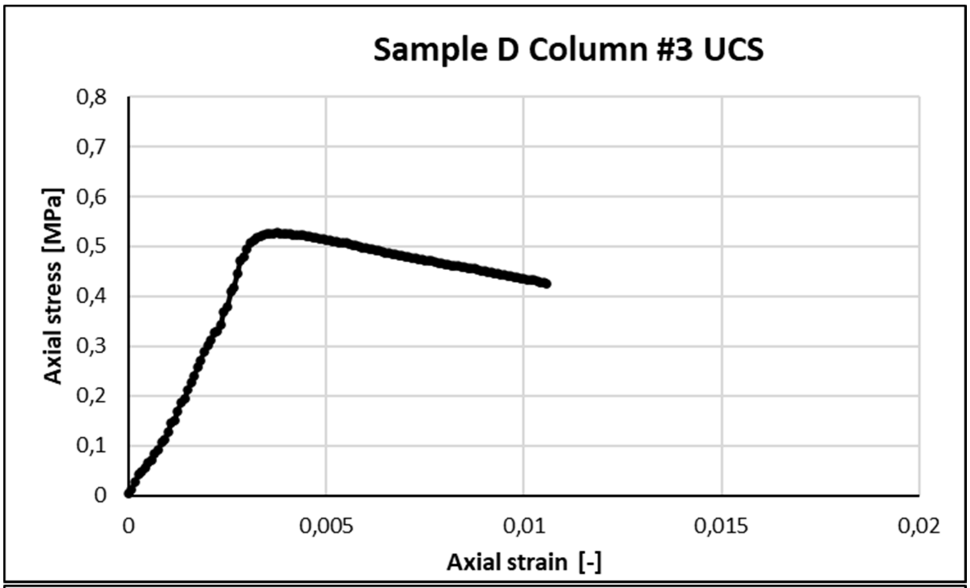
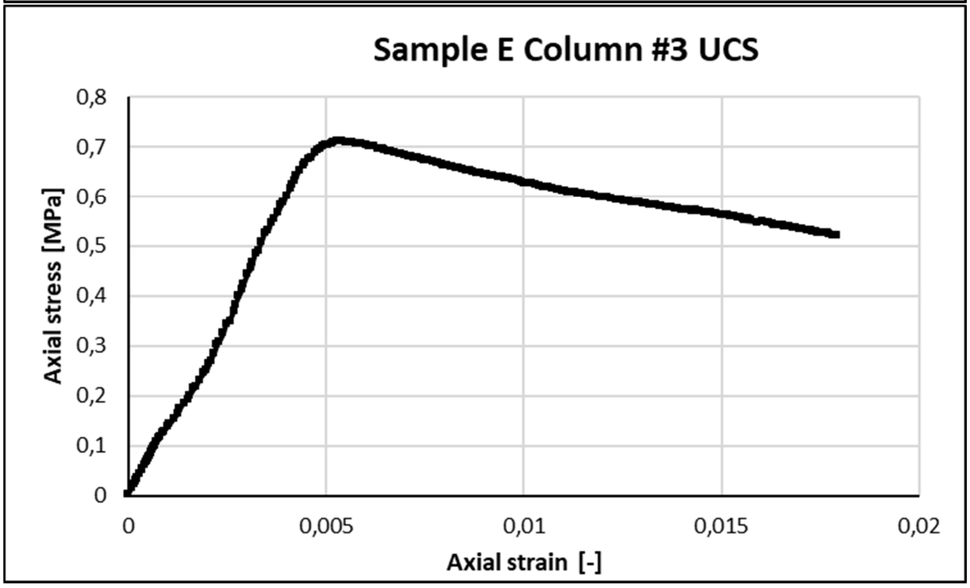


Figure 22: ax. stress – ax. strain graphs of samples from Column #1


Sample D Column #3 UCS
Axial stress [MPa]
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
0,005
0,01
0,015
0,02
Axial strain [-]


Sample E Column #3 UCS
Axial stress [MPa]
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
0,005
0,01
0,015
0,02
Axial strain [-]

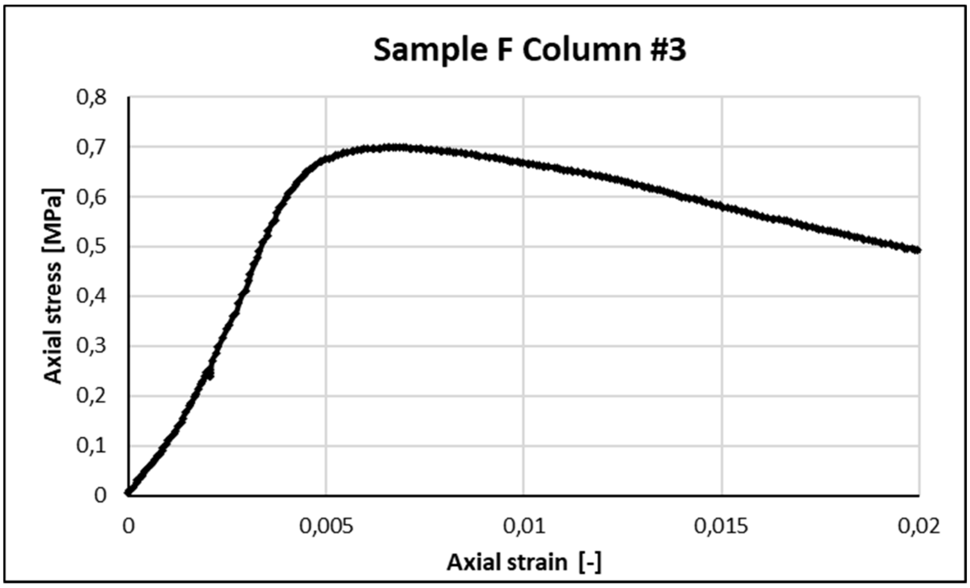
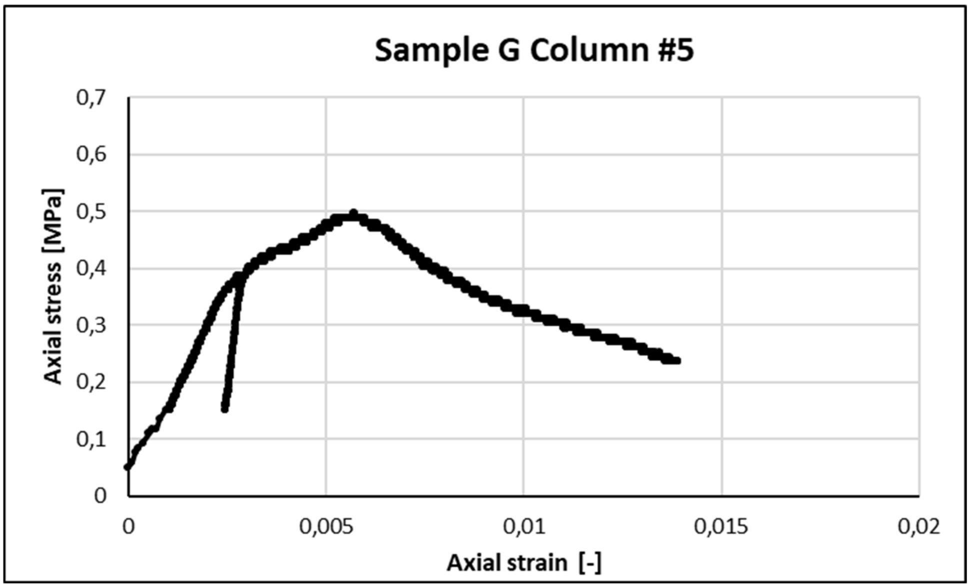
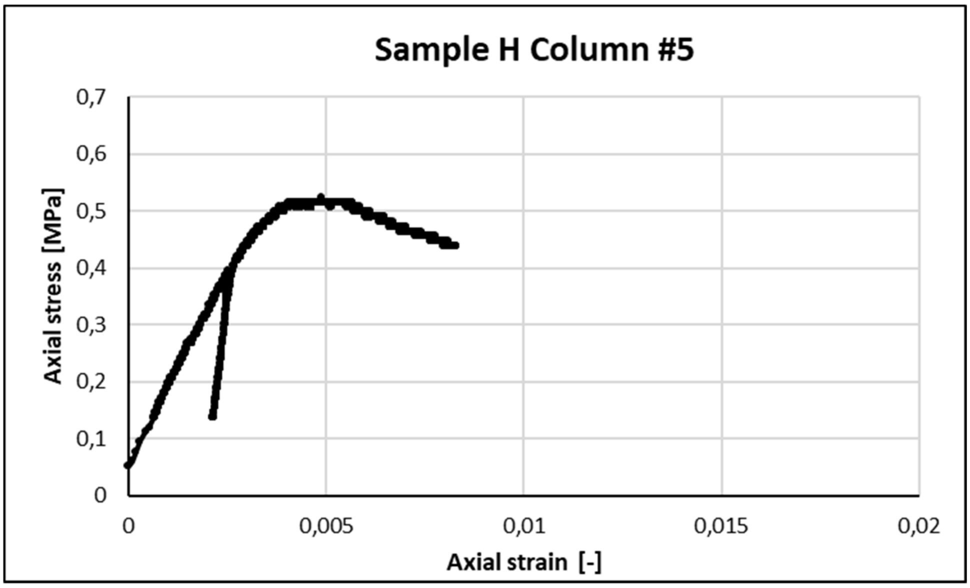


Figure 23: ax. stress – ax. strain graphs of samples from Column #3





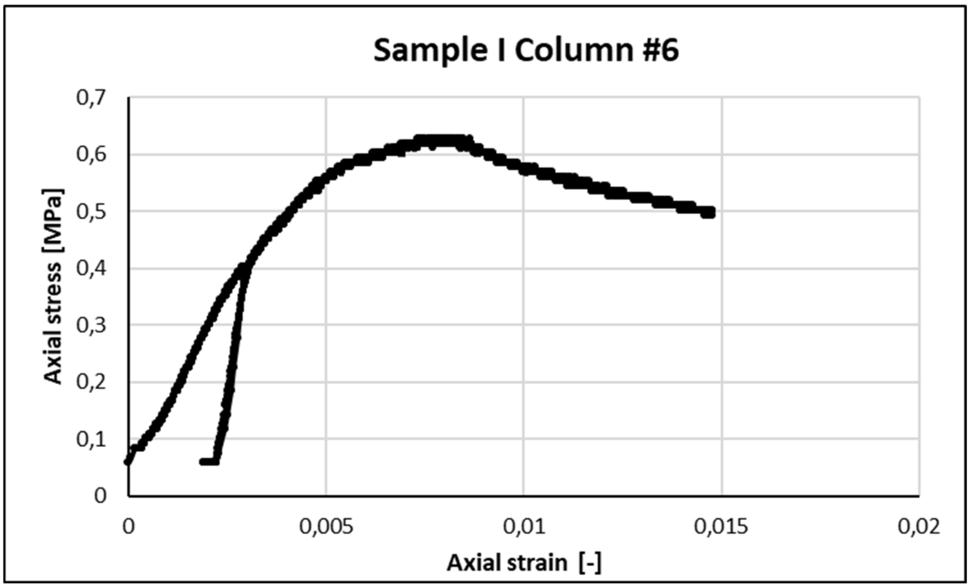
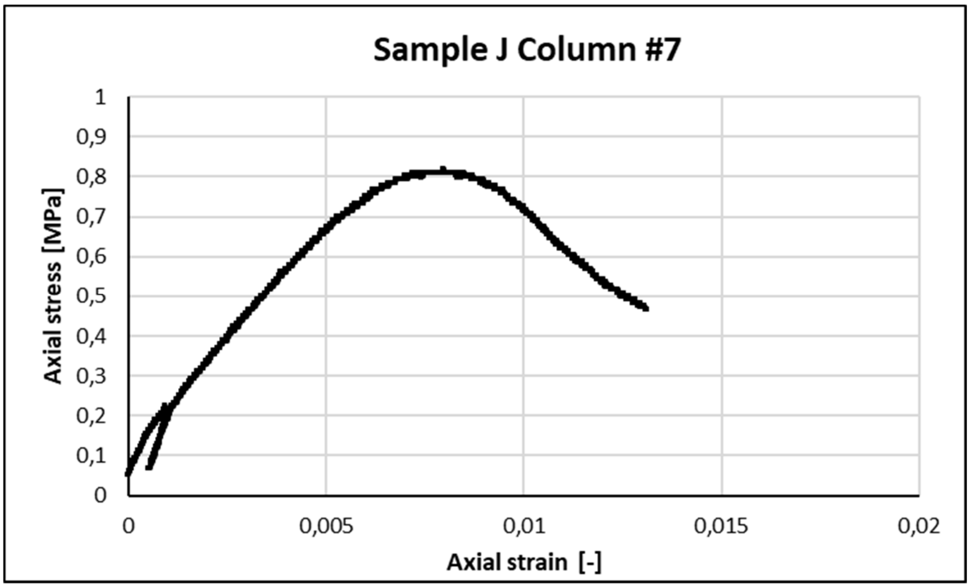
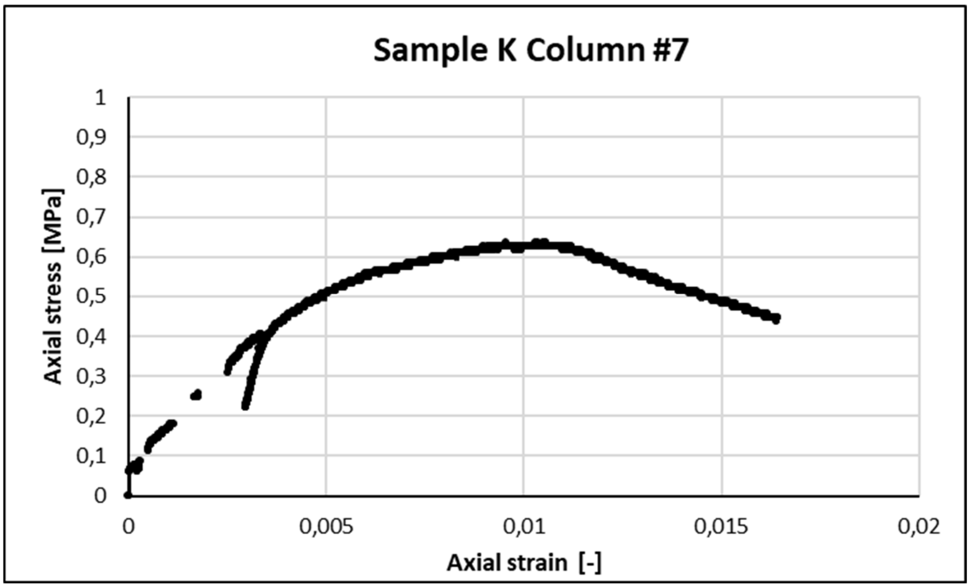


Figure 24: ax. stress – ax. strain graphs of samples from Column #5 and #6


Sample J Column #7
Axial stress [MPa]
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
0,005
0,01
0,015
0,02
Axial strain [-]


Sample K Column #7
Axial stress [MPa]
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0
0,005
0,01
0,015
0,02
Axial strain [-]

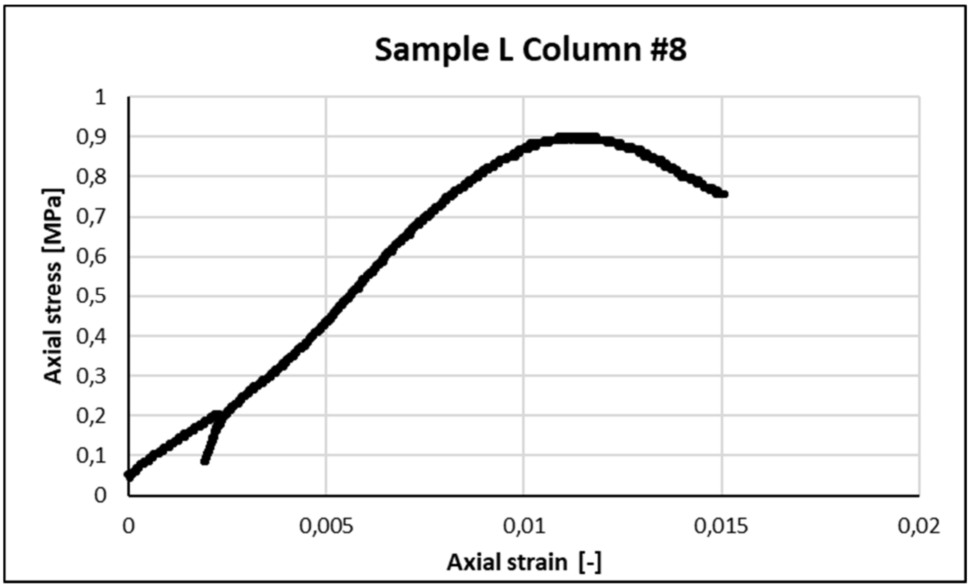


Figure 25: ax. stress – ax. strain graphs of samples from Column #7 and #8

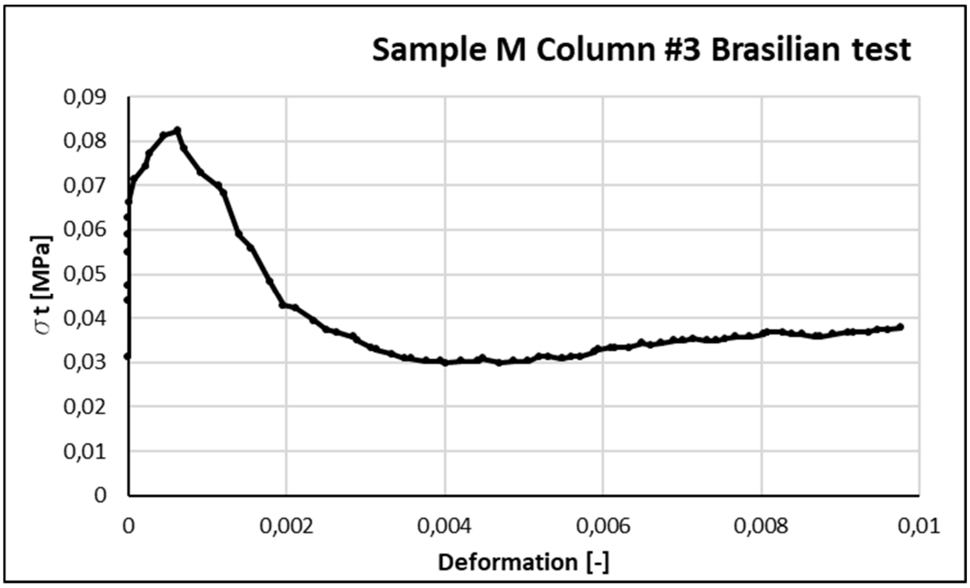
Sample	Column	Soil	Mixture	Distance from the base [cm]	Sample dimension			
					h [mm]	D [mm]	mass [g]	ρ [g/cm^3]
A	#1	Soil #1	Mixture #1	38 - 45	74	37	-	-
B	#1	Soil #1	Mixture #1	23 - 31	80	37	-	-
C	#1	Soil #1	Mixture #1	7 - 15	76	37	-	-
D	#3	Soil #2	Mixture #1	42 - 50	85	38,5	201,39	2,04
E	#3	Soil #2	Mixture #1	20 - 28	81	38,4	195,15	2,08
F	#3	Soil #2	Mixture #1	32 - 40	82	38,5	193,93	2,03
G	#5	Soil #3	Mixture #2	4,5 - 13	81,5	38,9	193,6	2,00
H	#5	Soil #3	Mixture #2	15 - 23	81	38,5	196,26	2,08
I	#6	Soil #3	Mixture #2	7 - 15	80	39	204,58	2,13
J	#7	Soil #4	Mixture #3	15 - 25	77	38,4	186,24	2,09
K	#7	Soil #4	Mixture #3	25 - 35	83	38,5	197,78	2,04
L	#8	Soil #4	Mixture #3	5 - 13	82	38,7	204,05	2,11

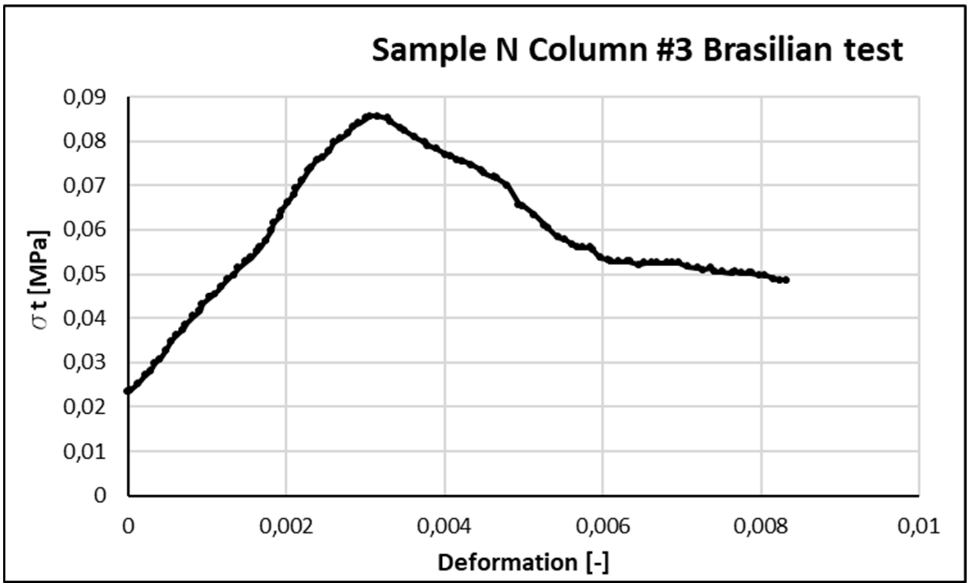
Sample	Test speed		Maturation time [gg]	σ_c [MPa]
	v [mm/min]	v [%/min]		
A	0,05	0,067	16	**0,59**
B	0,05	0,0625	21	**0,7**
C	0,025	0,033	40	**0,91**
D	0,425	0,5	28	**0,527**
E	0,405	0,5	28	**0,711**
F	0,41	0,5	28	**0,699**
G	0,015	0,018	28	**0,496**
H	0,015	0,018	28	**0,516**
I	0,015	0,019	28	**0,627**
J	0,015	0,019	28	**0,811**
K	0,015	0,018	28	**0,626**
L	0,015	0,018	28	**0,9**

Figure 26: data table UCS tests

4.5.2 Brazilian test

This test method concerns the determination of the splitting tensile strength of intact rock specimen, it’s a simple method to determine tensile strength. Tests are carried out in according to ASTM D3967 standard.





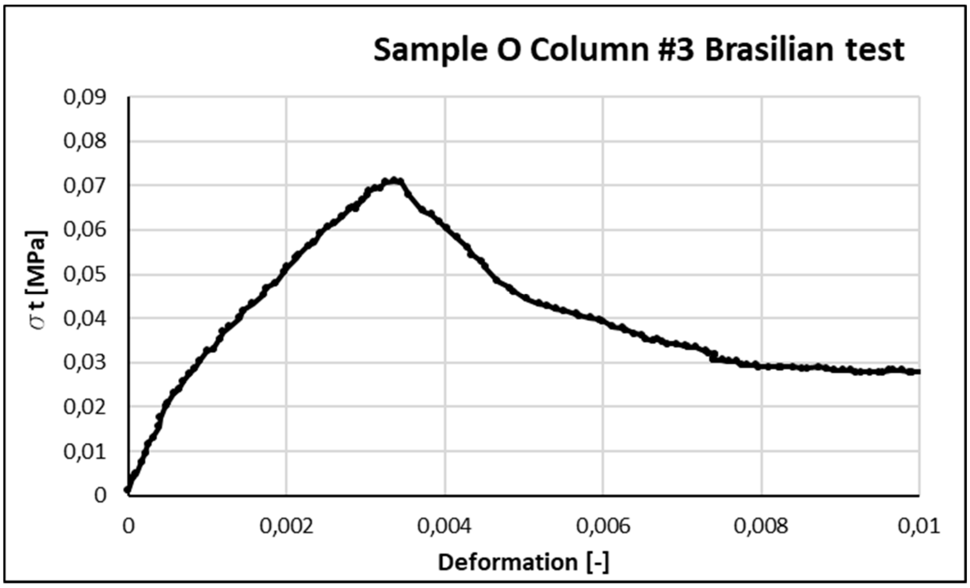


Figure 27: ax. tensile stress – strain graphs of samples from Column #3

Sample	Column	Soil	Mixture	Distance from the base [cm]	Sample dimension			
					h [mm]	D [mm]	mass [g]	ρ [g/cm^3]
M	#3	Soil #2	Mixture #1	3 - 5,5	21,5	38,3	48,12	1,94
N	#3	Soil #2	Mixture #1	14,5 - 17,5	27,5	38,4	62,79	1,97
O	#3	Soil #2	Mixture #1	28,5 - 31,3	27	38,4	62,77	2,01

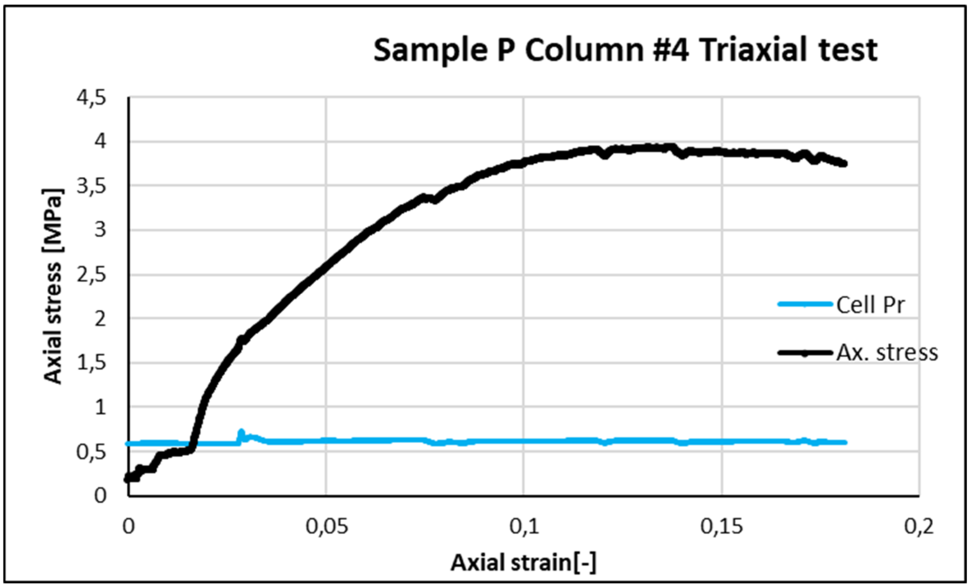
Sample	Test speed		Maturation time [gg]	σ_t [MPa]
	v [mm/min]	v [%def/min]		
M	0,383	1	30	**0,082**
N	0,192	0,5	30	**0,086**
O	0,192	0,5	30	**0,071**

Figure 28: data table of Brazilian tests

4.5.3 Triaxial test

This test method concerns the determination of Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils

Specimens are subjected to a confining fluid pressure in a triaxial chamber. No drainage is permitted during the test. The specimen is sheared in compression at a constant rate of axial deformation. Tests are carried out in according to ASTM D2850-03 standard.



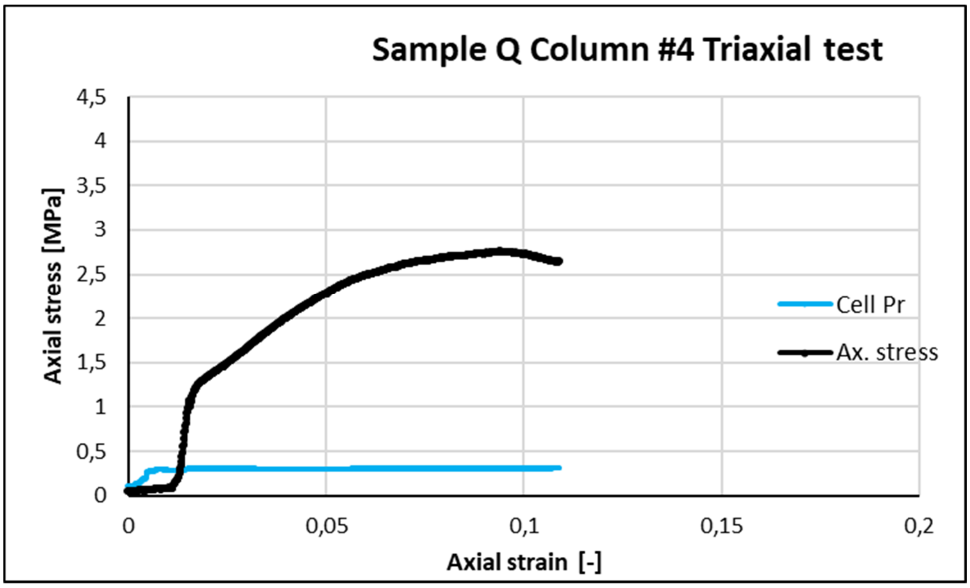


Figure 29: stress – strain graphs of samples from Column #4

Sample	Column	Soil	Mixture	Distance from the base [cm]	Sample dimension			
					h [mm]	D [mm]	mass [g]	ρ [g/cm^3]
P	#4	Soil #2	Mixture #1	5 - 13	80	38,3	190,91	2,07
Q	#4	Soil #2	Mixture #1	13,3 - 21,2	78,5	38,35	184,06	2,03

Sample	Test speed		Maturation time [gg]	σ_t [MPa]
	v [mm/min]	v [%def/min]		
0,6	0,75	32	**3,94**	**0,6**
0,6	0,76	32	**2,76**	**0,3**

Figure 30: data table of Triaxial tests

4.6 Choice of granular material

Conducting the column injection tests made it possible to verify from an experimental point of view, that the granular material called soil #5 is not injectable by the ternary mixtures water cement bentonite. The fine granular material called soil #4 was found to be injectable with mixture #3 (silicate mixture). The granular materials named soil #1, soil #2 and soil #3 are injectable by the ternary mixtures water cement bentonite, previously named mixture #1 and mixture #2.

The performance of the mechanical tests made it possible to assess the resistance that the soil develops following injection and curing; it can be seen from the tables above how the unconfined compressive strength

(UCS) values are similar for the different injected soils. Specifically, the UCS values are between 0.5 and 0.6 MPa after a post-injection curing time of 28 days.

Wanting to carry out injection tests of ternary water-bentonite cement mixtures, the choice of soil to be used in 3D injection tests fell on soil #2 given its injectability, the good mechanical characteristics of the consolidated samples, as well as its easy availability and low cost.

References Chapter 4

ASTM D4320-02 Standard Test Method for Laboratory Preparation of Chemically Grouted Soil Specimens for Obtaining Design Strength Parameters

ASTM D422 Standard Test Method for Particle-Size Analysis of Soils

UNI EN 1771 2005 Prodotti e sistemi per la protezione e la riparazione delle strutture di calcestruzzo - Metodi di prova - Determinazione dell'iniettabilità e della resistenza a trazione indiretta

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Zebovitz, S., Krizek, R. J., & Atmatzidis, D. K. (1989). Injection of fine sands with very fine cement grout. *Journal of geotechnical engineering*, *115*(12), 1717-1733.

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Santagata, M. C., & Santagata, E. (2003). Experimental investigation of factors affecting the injectability of micro cement grouts. In *Grouting and Ground Treatment* (pp. 1221-1234).

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Pettinaroli A., Caffaro P., Lodico M., Carrettucci A., (2019). The technical management of the permeation grouting works in the execution of the new Metro Line 4 in Milan, World Tunnel Congress 2019, Napoli.

Lombardi, G. (1999). Iniezioni di masse rocciose con miscele cementizie. Il concetto GIN. *Rivista Italiana di Geotecnica*.

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ASTM D2166 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil

ASTM D2850 Standard Test Method for Unconsolidated-Undrained Triaxial Compression Test on Cohesive Soils7

ASTM D3967 Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens

Chapter 5

Laboratory test: 3D injection test

5.1 Introduction

In this chapter, three-dimensional injection tests using the innovative cylindrical apparatus are presented and described. In these tests, the injection progress is monitored both indirectly, from the "outside", by measuring the injection parameters: volume, flow rate and pressure as per established practice (Pettinaroli et al., 2019), and directly, from the "inside", by means of thermocouple wires, which exploit the temperature difference between the soil and the injection mixture, to detect the passage of the mixture at certain points within the soil volume.

This series of tests is the most innovative, replicating in the laboratory a permeation grouting injection from a single valve of the manchette tube. In addition to the large soil sample and the radial injection from the manchette tube, a bentonite sheath is present between the soil and the TAM, and the injection is carried out using a mixer and site injector.

5.2 Injection test

The first three-dimensional injection tests were carried out with a diaphragm pump and water was injected, followed by injection tests with a ternary mixture of water cement and bentonite using the same diaphragm pump. Given the difficulty in many cases in breaking the sheath using the diaphragm pump, if not the impossibility, a piston injector, such as those used on the construction site, was purchased, and used to carry out the subsequent injection tests.

In all the injection tests carried out, the granular material used to make the soil sample to be treated is kept constant and is the material renamed Soil #2 in the previous chapter, which it's possible to see in the Figure 1.

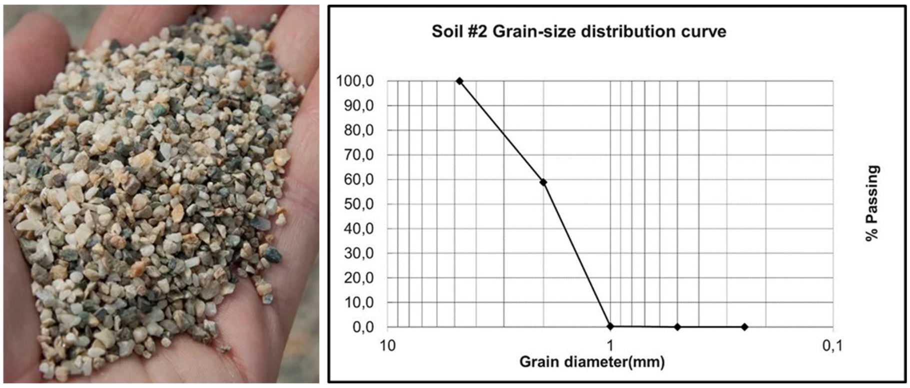


Figure 1: photo (on the left) and grain – size distribution curve (on the right) of soil #2

The ternary mixture used, consisting of water cement and bentonite plus the addition of a fluidising additive, always has the same mix design. This allows comparable data to be obtained during the different tests, as the density of the mixture, the Marsh Cone viscosities and more generally the rheological behaviour do not change.

Injection ternary mixture			
Material	**Type**	**Quantity**	**u.m.**
Water	Aqueduct	100	kg
Cement	Ultracem 52.5	40	kg
Bentonite	Bentogel Y	3,4	kg
Additive	Lamsperse BV	0,35	kg

Figure 2: ternary mixture mix design.

A1) Confezionamento miscela

Acqua	62,65 kg
Cemento	25 kg
Bentonite	2,13 kg
Additivo	0,22 kg

T acqua	26 °C

A2) Densità (API RP 13B-1 2003)

Temperatura	33 °C
Peso di volume	**1,231 kg/lt**

A3) Viscosità al cono di Marsh (API RP 13B-1 2003)

Durata	**35 sec**

A4) Viscosità inziale con viscosimetro rotativo tipo Rheometer (API RP 13-1 2003)

Temperatura	33 °C	Viscosità plastica VP	**6,0 cP**
L300	9 RPM	Coesione YP	**1,4 Pa**
L600	15 RPM	Viscosità apparente VA	**7,5 cP**

A6) Stabilità alla decantazione (API RP 13B-1 2003)

1h	100 %
2h	100 %
3h	**100 %**

Figure 3: ternary mixture rheological characteristics

For the bentonite sheath, that fills the annular volume between the manchettes pipe and the surrounding soil, a single mix design is used, shown below.

Bentonitic sheath			
Material	**Type**	**Quantity**	**u.m.**
Water	Aqueduct	100	kg
Cement	32.5	50	kg
Bentonite	Bentogel Y	5	kg

Figure 4: bentonite sheath mix design

For each test, soil thickening characteristics, data recorded by the injector, data acquired by recording thermocouples are reported.

If treated soil is allowed to consolidate, a bulb of cemented soil is obtained at the end of curing. Operations were carried out on the bulb to determine its volume; two different types of surveys were carried out on each bulb: photogrammetric survey (TDP) and survey with Terrestrial Laser Scanner (TLS).

Both remote acquisition techniques make it possible to obtain georeferenced point clouds, from which it is possible to construct a three-dimensional mesh and create a 3D model to calculate the volume of the desired object. LiDAR directly returns the 'dense cloud', while photogrammetry first requires image alignment using dedicated software. The software chosen in this case for constructing the model and calculating the volume from the two technologies is Agisoft Metashape Professional (Agisoft site).

Terrestrial Digital Photogrammetry

The Terrestrial Digital Photogrammetry (TDP) is a technique that makes it possible to determine the 3D coordinates of points in a reference system from their 2D coordinates on photographic images, obtaining a cloud of points (dense cloud), from which it is possible to construct a 3D model of the 'feature' of interest. To identify the points in three dimensions, it is necessary to know the position of the camera and/or several targets on the scene, i.e., known points through which the resulting point cloud can be georeferenced.

The technique consists in taking a series of high-resolution photographs at successive camera positions, with an overlap between them of at least 60%, covering, as far as possible, the entire surface of the feature of interest.

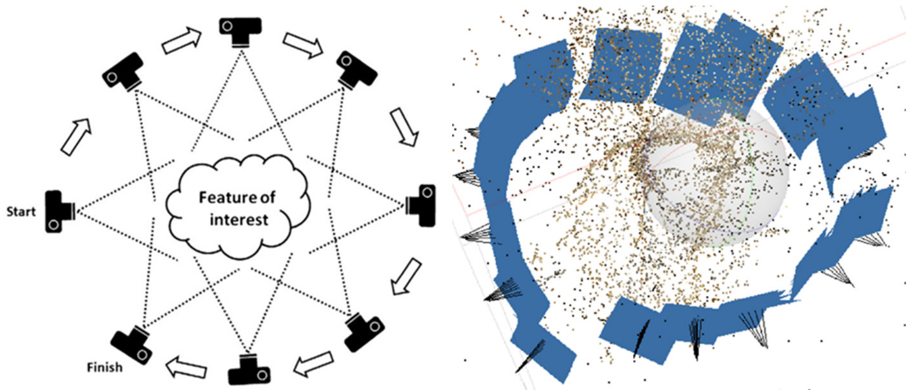


Figure 5: Digital Terrestrial Photogrammetry Technique

Terrestrial Laser Scanner

The TLS technique is performed using LiDAR (Light Detection And Ranging) technology. It consists of the remote acquisition, using devices called laser scanners, of point clouds derived from the feature of interest, to which XYZ coordinates and reflectance values are assigned.

Laser scanners emit laser pulses and measure the distance from the point of interest to the device, calculating the arrival time and phase difference of the reflected waves. The coordinate system in this case is relative to the laser scanner, which acts as the point of origin.

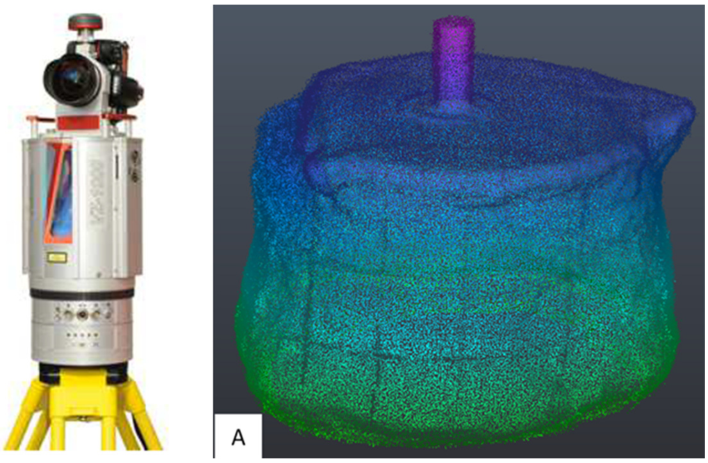


Figure 6: a laser scanner is shown on the left. On the right is an example of a LiDAR survey.

5.2.1 Water injection #1

In the first injection test carried out using the cylindrical machinery, water was injected into the ground using the sleeve tube, the sheath was not thrown around the tube.

A diaphragm pump was used to pump the water, the total volume injected is 20 liters.

The packer was not used, the tube has a glued and threaded cap to which the delivery tube is connected.

The mechanical seal between the TAM and the cover is given by a flange fitted on the tube and fixed to the cover by means of threaded bars, contrasts and bolts.

The soil sample has been thickened to 60% of Dr, this value corresponds to a density of 1.52 kg / l for a total of 198 kg.

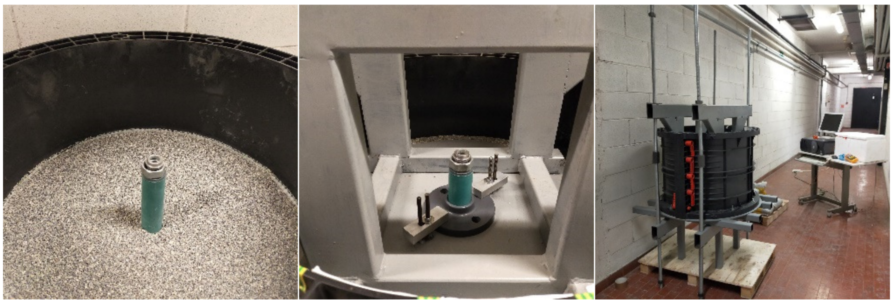


Figure 7:Cylindrical machine, soil sample around the TAM (on the left), the top of the machine (at the centre), complete view of machine (at the right)

Thermocouples

Six thermocouples are placed inside the soil sample, are arranged at two heights with respect to the bottom (10 cm and 14 cm) and at different radial distances from the tube (7, 14 and 25 cm), they are all contained within the same plane. Signal acquisition is carried out using Datascan 7220.

Results

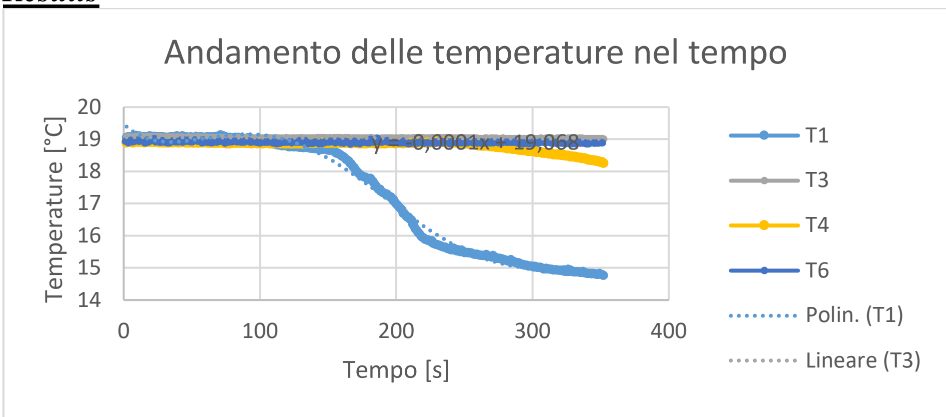


Figure 8: trend of temperatures over time

	h[cm]	r[cm]	t [s]
T1	10	7	85
T2	10	14	-
T3	10	25	-
T4	14	7	237
T5			
T6	14	14	-

Figure 9: thermocouples position and time of arrivals

A temperature variation is recorded by the thermocouples T1 (85 seconds) and T4 (237 seconds) placed at a radial distance of 7 cm from the tube and at a height of 10 and 14 cm respectively from the bottom.

This test proved that thermocouples could record the passage of a fluid within the soil sample, if the injected fluid has a different temperature from that of the soil itself.

5.2.2 Water injection #2

During the second test, no changes are introduced with respect to the first test about the composition of the soil sample and the amount of water injected; instead, the number of thermocouples placed inside the sample is increased to carry out the front passage measurements.

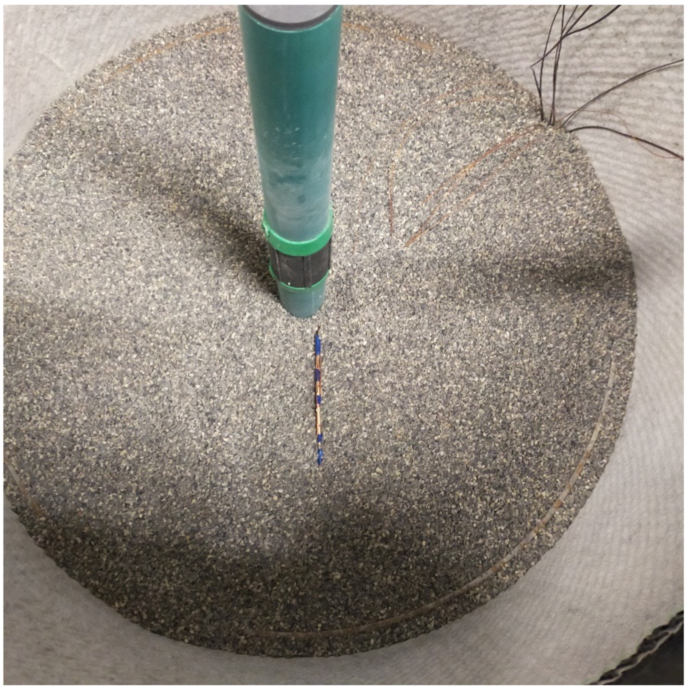


Figure 10: soil sample and thermocouples

Thermocouples

The 15 thermocouples placed inside the soil sample are arranged at three heights with respect to the bottom (5, 15 and 22.5 cm) and at different radial distances from the pipe (3, 5, 7, 9, 11 and 13 cm), they are all contained within the same plane, signal acquisition is carried out using Datascan 7220.
Thermocouples number 4, 12, 13 and 15 did not work, the recorded data came from the other eleven thermocouples.

Results

Data were acquired from 11 thermocouples, arranged along a plane, within the soil sample. It was possible to identify after how long, from the start of injection, the injection front reaches the point within the sample identified by the presence of the thermocouple. As was to be expected, the points closest to the injection valve are the first to register the arrival of the water.

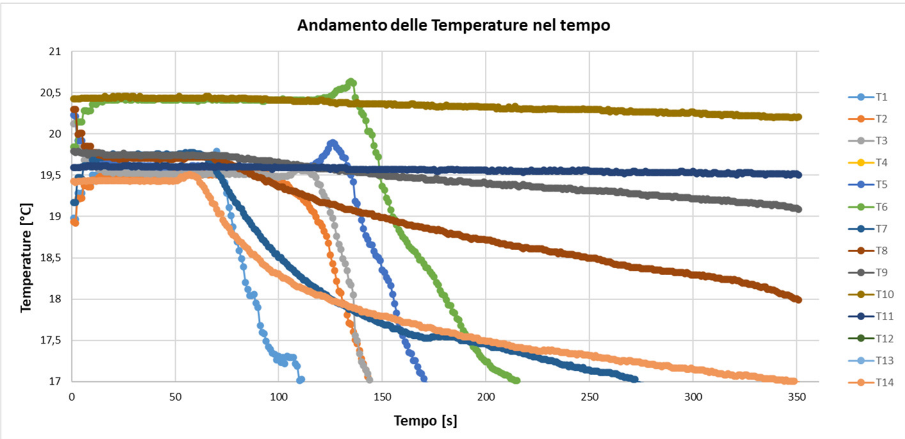


Figure 11: trend of temperature over time

	h[cm]	r[cm]	t [s]
T1	5	3	32
T2	5	5	58
T3	5	7	78
T4			-
T5	5	11	87
T6	5	13	96
T7	15	3	18
T8	15	5	25
T9	15	7	37
T10	15	9	45
T11	15	11	91
T12			-
T13			-
T14	22,5	3	19
T15			-

Figure 12: thermocouples position and time of arrivals.

5.2.3 Cement mixture injection #1

The sand sample was compacted in the cylindrical apparatus to a density of 1.56 kg/l, in the centre of the sample around the manchettes tube, the bentonite sheath was cast. The seal between the manchettes tube and the lid is provided by a flange.

After the sheath had cured for one day, the injection of consolidation mixture was carried out.

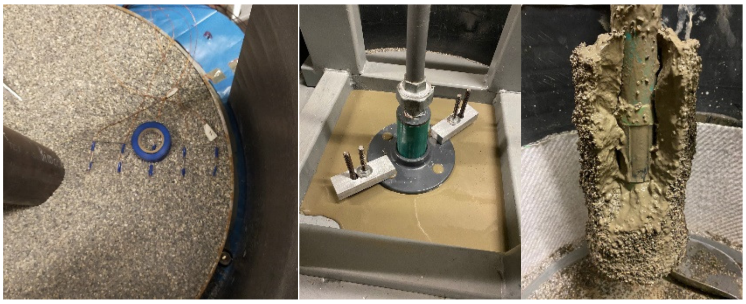


Figure 13: soil sample and thermocouples (on the left), cement mixture flow out to the machine (at the centre), bentonitic sheath after injection (on the right)

Thermocouples

The 15 thermocouples placed inside the soil sample are arranged at three heights with respect to the bottom (5, 15 and 22.5 cm) and at different radial distances from the sheath (5, 10, 15, 20 and 25 cm), they are all contained within inside the same plane, the position of each thermocouple is indicated in the table below. The acquisition of the signal is carried out using Datascan 7220.

Results

About two liters of mixture escaped from the flange that fixes the tube to the lid and flowed onto the lid itself.

At the end of the test the machine was opened, and it was possible to observe that about a 5 cm cylindrical band around the sheath was injected and in fact only thermocouples T10 and T15, located 5 cm from the sheath, recorded a temperature variation. There was significant leakage of mixture along the contact surface between the lid and flange as can be clearly seen in Figure 13 .

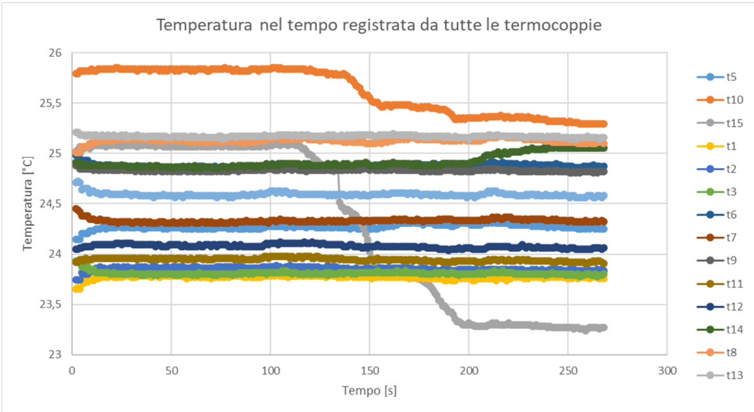


Figure 14: trend of temperatures over time

	h[cm]	r[cm]	t [s]
T1	5	25	-
T2	5	20	-
T3	5	15	-
T4	5	10	-
T5	5	5	-
T6	15	25	-
T7	15	20	-
T8	15	15	-
T9	15	10	-
T10	15	5	138
T11	22,5	25	-
T12	22,5	20	-
T13	22,5	15	-
T14	22,5	10	-
T15	22,5	5	115

Figure 15: thermocouples position and time of arrivals.

5.2.4 Cement mixture injection #2

The 195 kg sample of sand was compacted in the cylindrical apparatus to a density of 1.56 kg/l. In the centre of the sample around the manchettes tube, the bentonite sheath was cast. The seal between the manchettes tube and the lid is provided by a flange, below which a rubber gasket is placed to prevent leakage of the mixture, which occurred in the previous test.

After the sheath had cured for one day, the injection of consolidation mixture was carried out.

Thermocouples

The 15 thermocouples placed inside the soil sample are arranged at three heights with respect to the bottom (5, 15 and 22.5 cm) and at different radial distances from the sheath (0, 5, 10, 15, 20 cm), they are all contained within inside the same plane. Signal acquisition is carried out using Datascan 7220.

Results

The mixture permeated an approximately cylindrical volume of soil with a radius of 6 cm beyond the sheath. Part of the mixture leaked at the interface between the manchettes tube and the sheath and spread over the soil and under the cover, as can be seen in the photos below.

Figure 16: mixture flow above the top of sample

Figure 17: mixture flowed over the top (on the left), mixture penetrate soil (on the right)

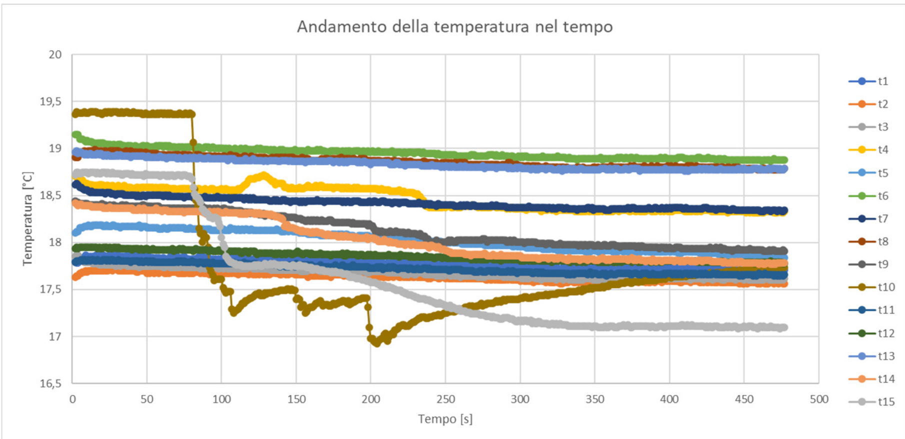


Figure 18: Trend of temperature over time

	h[cm]	r[cm]	t [s]
T1	5	20	-
T2	5	15	-
T3	5	10	-
T4	5	5	220
T5	5	0	150
T6	15	20	-
T7	15	15	-
T8	15	10	-
T9	15	5	102
T10	15	0	80
T11	22,5	20	-
T12	22,5	15	-
T13	22,5	10	-
T14	22,5	5	125
T15	22,5	0	80

Figure 19: thermocouples position and time of arrivals.

5.2.5 Conclusions regarding the first injection tests

The first four injection tests showed how the cylindrical three-dimensional injection apparatus, in a medium-scale soil sample, can simulate the reality in situ with the use of the valved tube to carry out the injections and the presence of the sheath. The soil sample is reconstituted in the laboratory, grain size, density and porosity are variables that are controlled and decided by the experimenter. It is possible to take measurements with thermocouples, placed inside the soil, which indicate the passage or non-passage of the mixture from a given point.

These preliminary tests made it possible to adapt the structure to the experimental evidence, improving all those details that showed defects that made the experimental injection deviate from the ideal one.

The need to use a piston injector, a tool used in situ to perform permeation grouting injections, was highlighted. With such a tool, higher pressures, necessary to break the sheath, can be achieved and the operator has control over the flow rate and not, only, the pressure. In this way, the mixture can be injected with the flow rates and pressures typical of a real case. In addition, this instrument can record the values of injected volume, pressure and flow rate over time, and this data can then be graphed and analysed.

5.2.6 Cement mixture injection #3

Test carried out with the cylindrical machine, the cement mixture was injected into the soil using the manchettes tube, around it is the bentonite sheath.

A piston injector was used to pump the mixture, as for in-situ injections, the total volume of the packaged mixture is 72 litres, while 30 litres are expected to be injected. A packer was not used to inject the mixture inside the manchettes tube, but the TAM with a glued and threaded cap to which the delivery tube is connected was used instead.

The mechanical seal between the TAM and the lid is provided by a flange mounted on the tube and fixed to the lid by means of threaded rods, contrasts and bolts and a rubber gasket.

Inside the cylindrical apparatus, 200 kg of granular material was compacted, for a density of 1.57 kg / l.

Thermocouples

The 15 thermocouples placed inside the soil sample are arranged at three heights with respect to the bottom (5, 15 and 22.5 cm) and at different radial distances from the sheath (0, 5, 10, 15, 20 cm), they are all contained within inside the same plane. Signal acquisition is carried out using Datascan 7220.

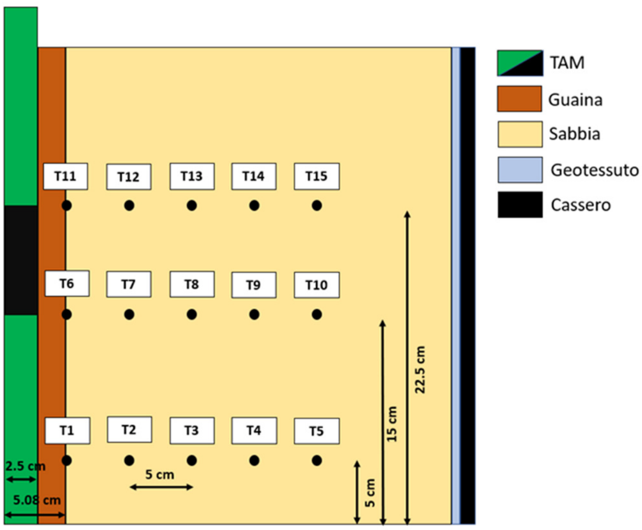


Figure 20: schematic diagram of thermocouple placement in the ground

Results

The injection failed, during the sheath rupture phase the pressure reached 16 bar. Before the sheath, the cap that was put on the injection tube was detached. The mixture has leaked out of the tube.

Figure 21: cylindrical machine, on the left it's possible to see the casing for bentonite sheath, on the right the top of machine.

Figure 22: cylindrical machinery (on the left) and injector (on the right)

Figure 23: TAM without cap (on the left), the cap detached from the mixture pressure (on the right)

5.2.7 Cement mixture injection #4

The previously prepared soil sample is injected the following week; a double packer was inserted inside the valved tube to complete the operation.

Figure 24: double packer and a tube a manchettes

Results

Injection of cement mixture, using the injector and double packer inside the TAM, is successful and 29 litres of mixture are pumped by the injector, the values of injected volume and pressure are recorded by the injector and graphed.

Thermocouples T2, T6, T7, T8, T11, T12 and T13 measure a notable change in temperature. The T1 thermocouple does not record temperature variation as it probably remains inside the bentonite sheath.

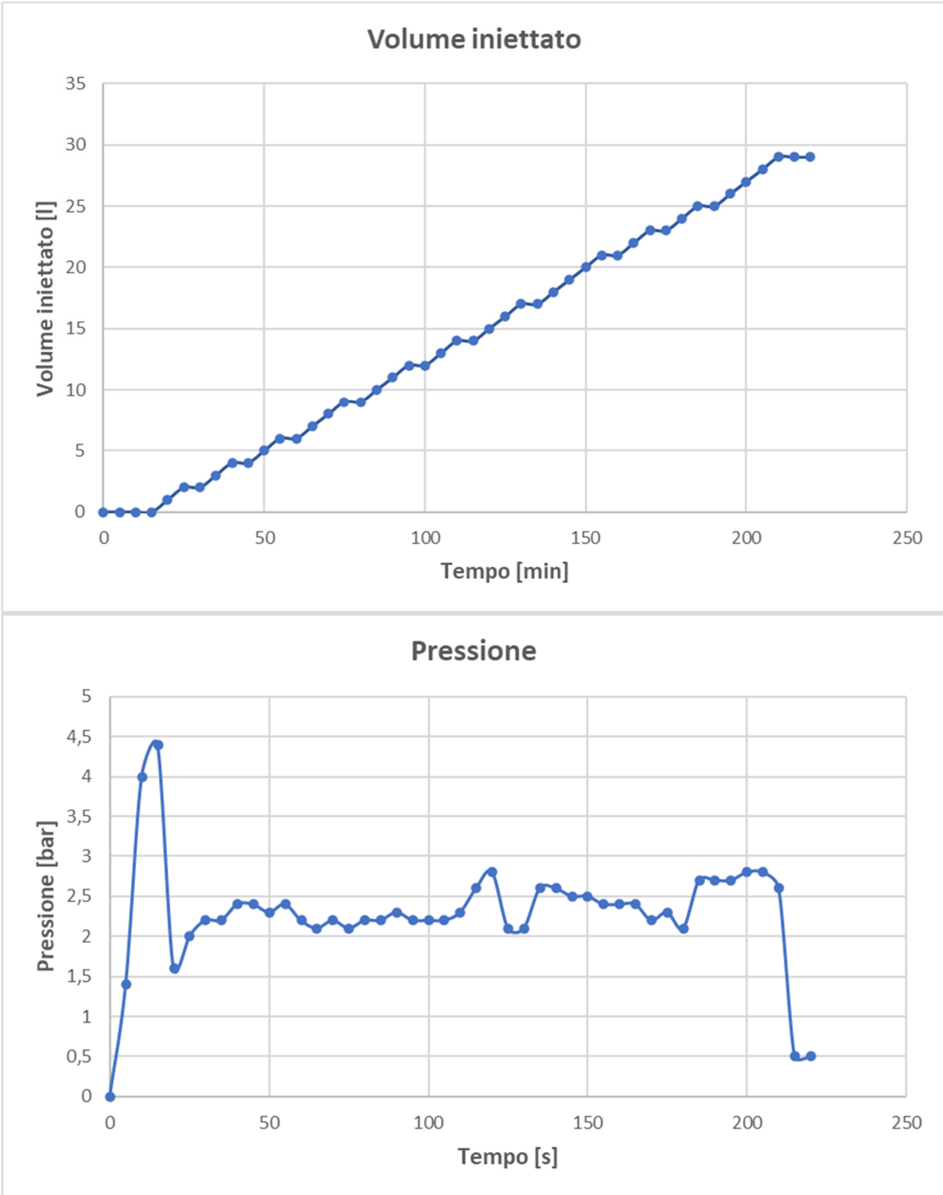


Figure 25: Graphs of injected volume and pressure over time, data acquired by injector.

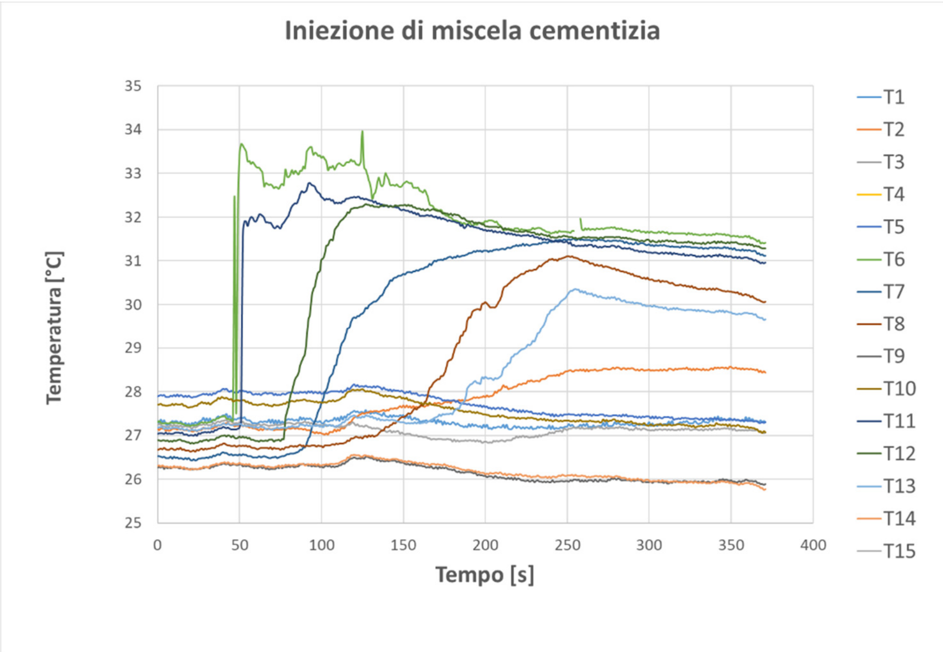


Figure 26: trend of temperature over time

	h[cm]	r[cm]	t [s]
T5	5	20	
T4	5	15	
T3	5	10	
T2	5	5	108
T1	5	0	
T10	15	20	
T9	15	15	
T8	15	10	110
T7	15	5	76
T6	15	0	47
T15	22,5	20	
T14	22,5	15	
T13	22,5	10	165
T12	22,5	5	78
T11	22,5	0	52

Figure 27: thermocouples position and time of arrivals.

From the results obtained and by normalising the temperature values, it is possible to derive the propagation profile of the mixture and simulate the extent of treatment.

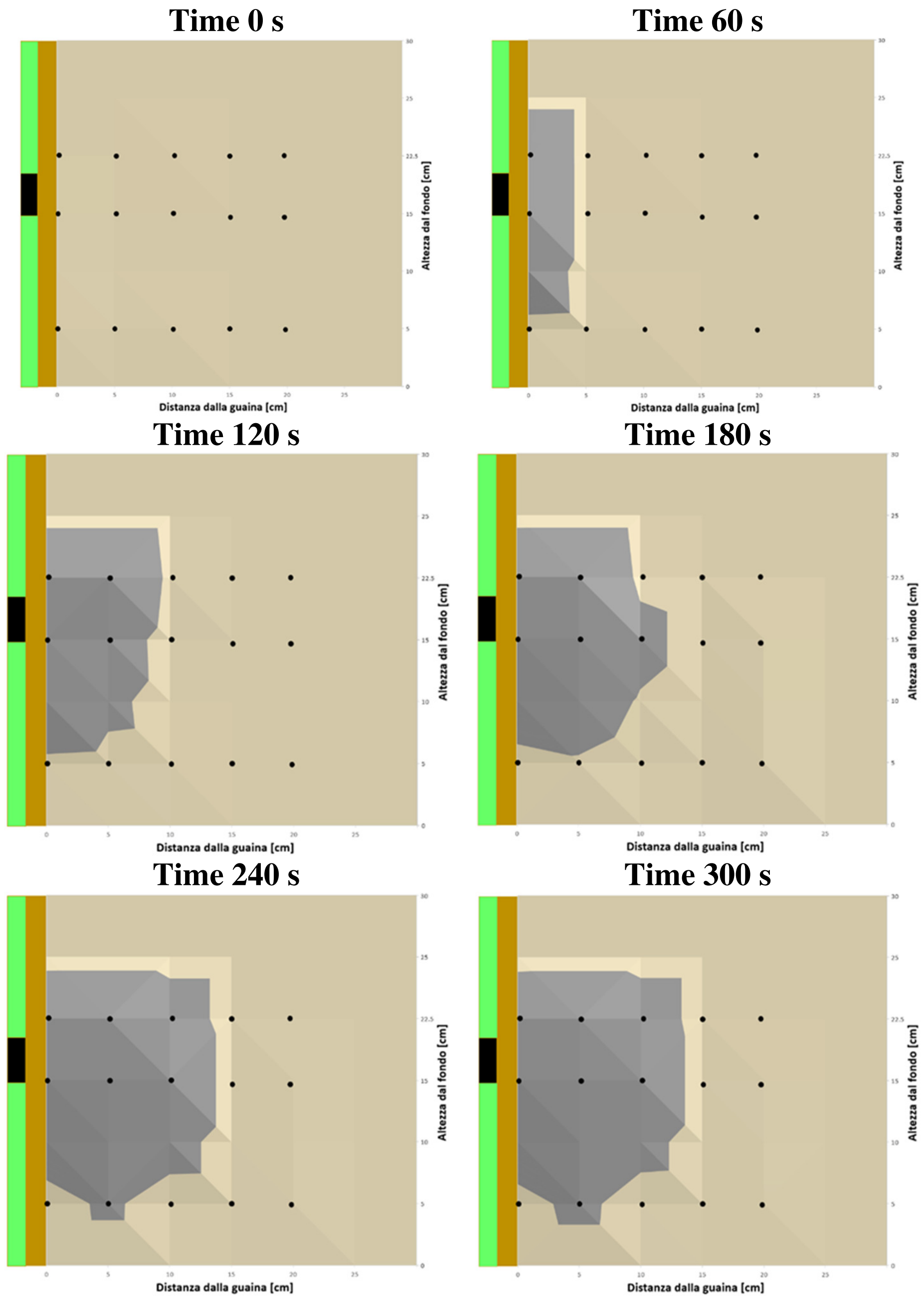


Figure 28: propagation of the mixture in the soil sample during the injection

<u>Consolidated soil bulb</u>

The treated soil is left to cure, and the bulb of consolidated material is obtained. The volume of the bulb is determined by carrying out a photogrammetric survey and a terrestrial laser scanner survey.

To carry out the photogrammetric survey, 84 photographs of the bulb were taken, with the help of Agisoft software the 3D model was created and the bulb volume of 68.3 liters was calculated.

For the laser scanner survey, six measurements were taken, the 3D model was created using Agisoft software, and the volume of the bulb was calculated to be 66.4 litres.

Figure 29: cemented soil volume

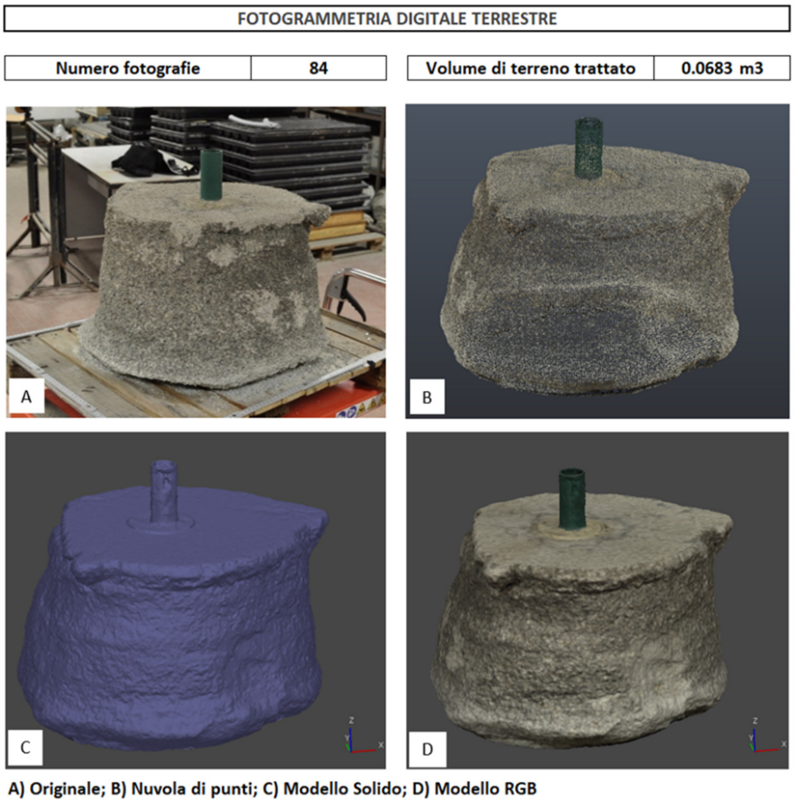


Figure 30: results of the photogrammetry performed on the treated soil block of the test cement mixture injection #4

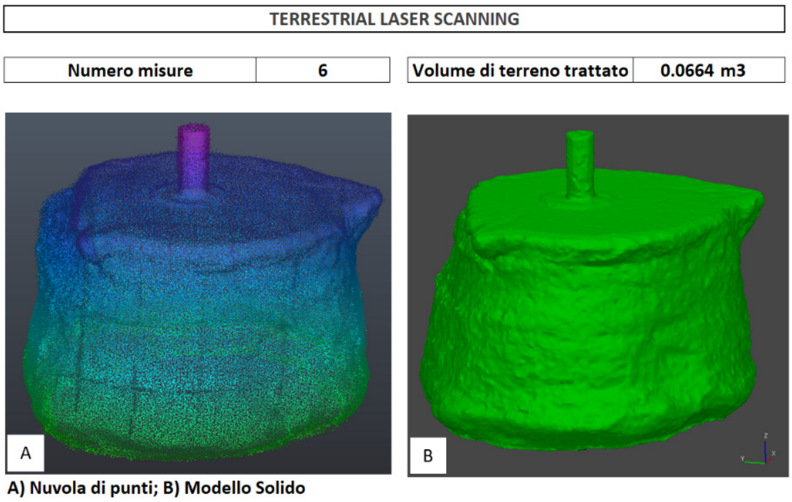


Figure 31: results of TLS survey

5.2.8 Cement mixture injection #5

Test carried out using the cylindrical machinery, cement mixture was injected into the ground using the sleeve tube. The sheath has been cast.

A piston injector was used for pumping the mixture, as per in situ injections, the total volume of the packaged mixture is equal to 72 liters, while it is planned to inject 30 liters. The double packer was used.

The mechanical seal between the TAM and the cover is given by a metal flange that contains the pipe and inside which the bentonite sheath is thrown to prevent the passage of mixture between pipe and sheath. The flange is fixed to the cover by means of threaded rods and bolts.

187 kg of granular material was compacted inside the cylindrical apparatus, for a density of 1.48 kg/l.

Figure 32: Cylindrical machine (on the left), injector & turbo mixer (on the right)

Figure 33: metal flange for augmented bentonite sheath load

Thermocouples

The 26 thermocouples placed inside the soil sample are arranged at 5 heights with respect to the bottom (5, 10, 15, 20 and 25 cm) and at different radial distances from the sheath (0, 5, 10, 15, 20 and 25 cm), they are all contained within the same plane, the position of each thermocouple is indicated in the table below. The acquisition of signals is carried out using the Bleb system for thermocouples from T1 to T16 and Datascan 7220 for thermocouples from T17 to T26.

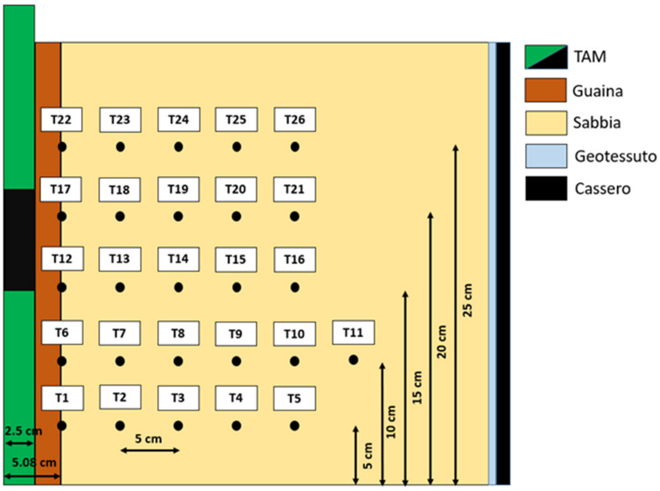


Figure 34: schematic diagram of thermocouple placement in the ground

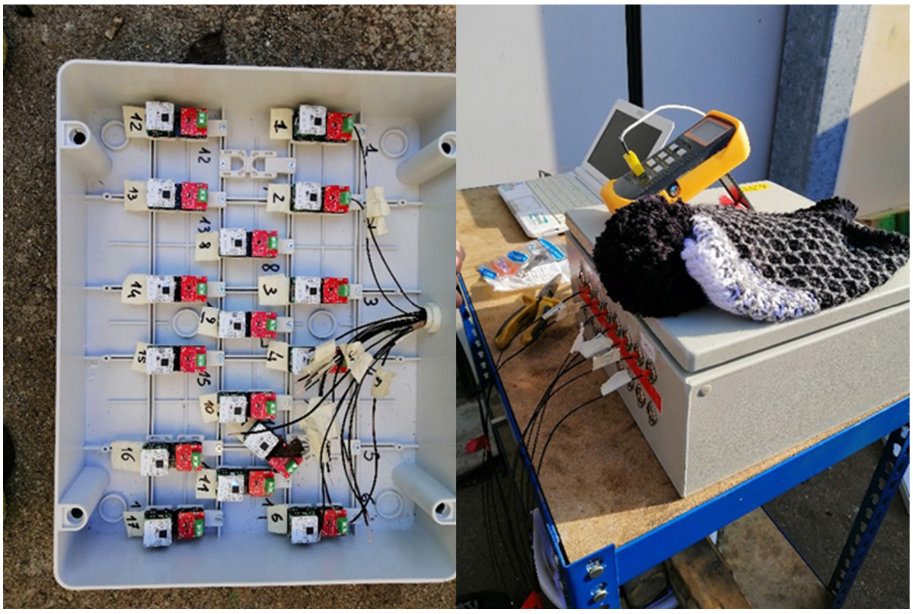
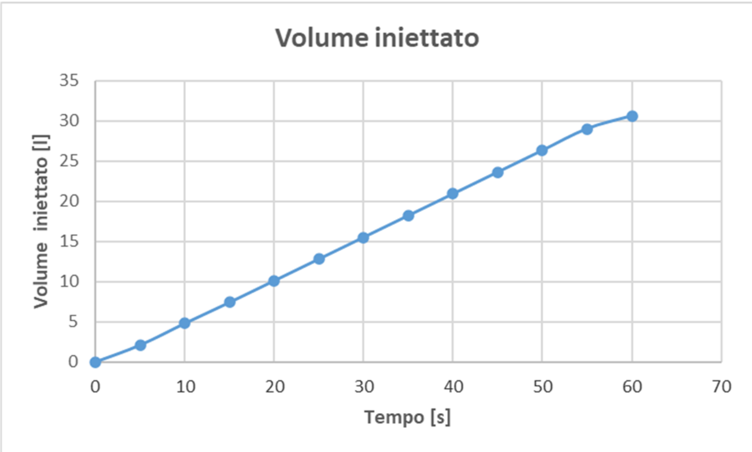


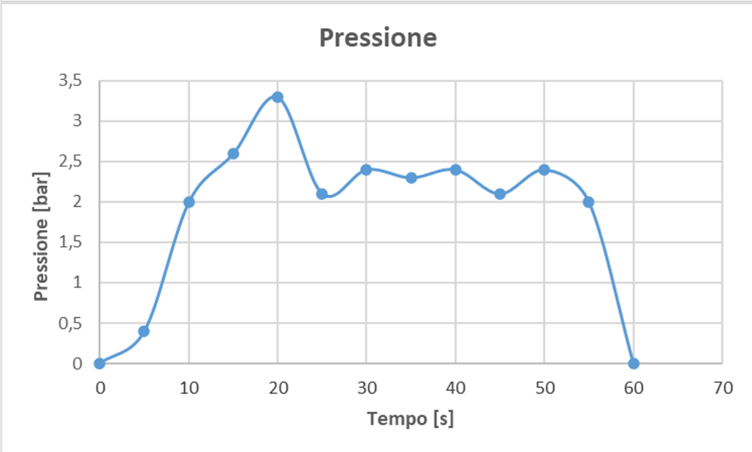
Figure 35: Bleb acquisition system (on the left), Datascan 7220 acquisition (on the right)

Results

In this test 29 liters are injected; the mixture is allowed to mature to obtain a cemented soil bulb. The injection parameters: injected volume, pressure and flow rate, over time, are recorded by the injector.

The temperature values, inside the ground, are detected using thermocouples. During the test, the thermocouples that record the temperature variation are those placed at the radial distances of 0, 5 and 10 cm.





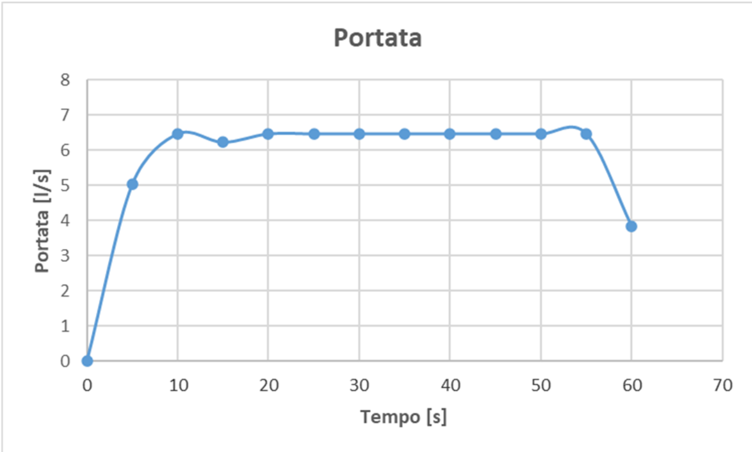


Figure 36: trends of volume, pressure, and flow rate over time

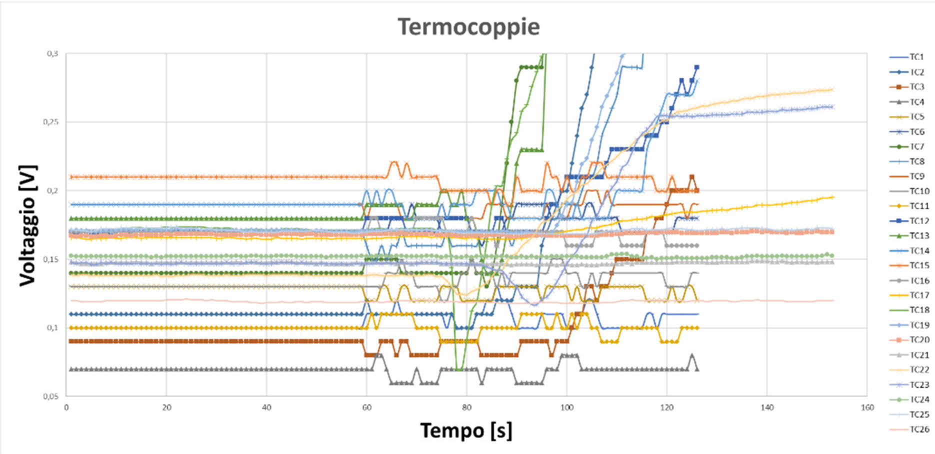


Figure 37: trend of voltage over time

	h[cm]	r[cm]	t [s]
T1	5	0	
T2	5	5	86
T3	5	10	101
T4	5	15	
T5	5	20	
T6	10	0	
T7	10	5	85
T8	10	10	95
T9	10	15	
T10	10	20	
T11	10	25	
T12	15	0	96
T13	15	5	86
T14	15	10	108
T15	15	15	
T16	15	20	

	h[cm]	r[cm]	t [s]
T17	20	0	94
T18	20	5	79
T19	20	10	98
T20	20	15	
T21	20	20	
T22	25	0	81
T23	25	5	95
T24	25	10	
T25	25	15	
T26	25	20	

Figure 38: thermocouples position and time of arrivals

From the results obtained and by normalising the temperature values, it is possible to derive the propagation profile of the mixture.

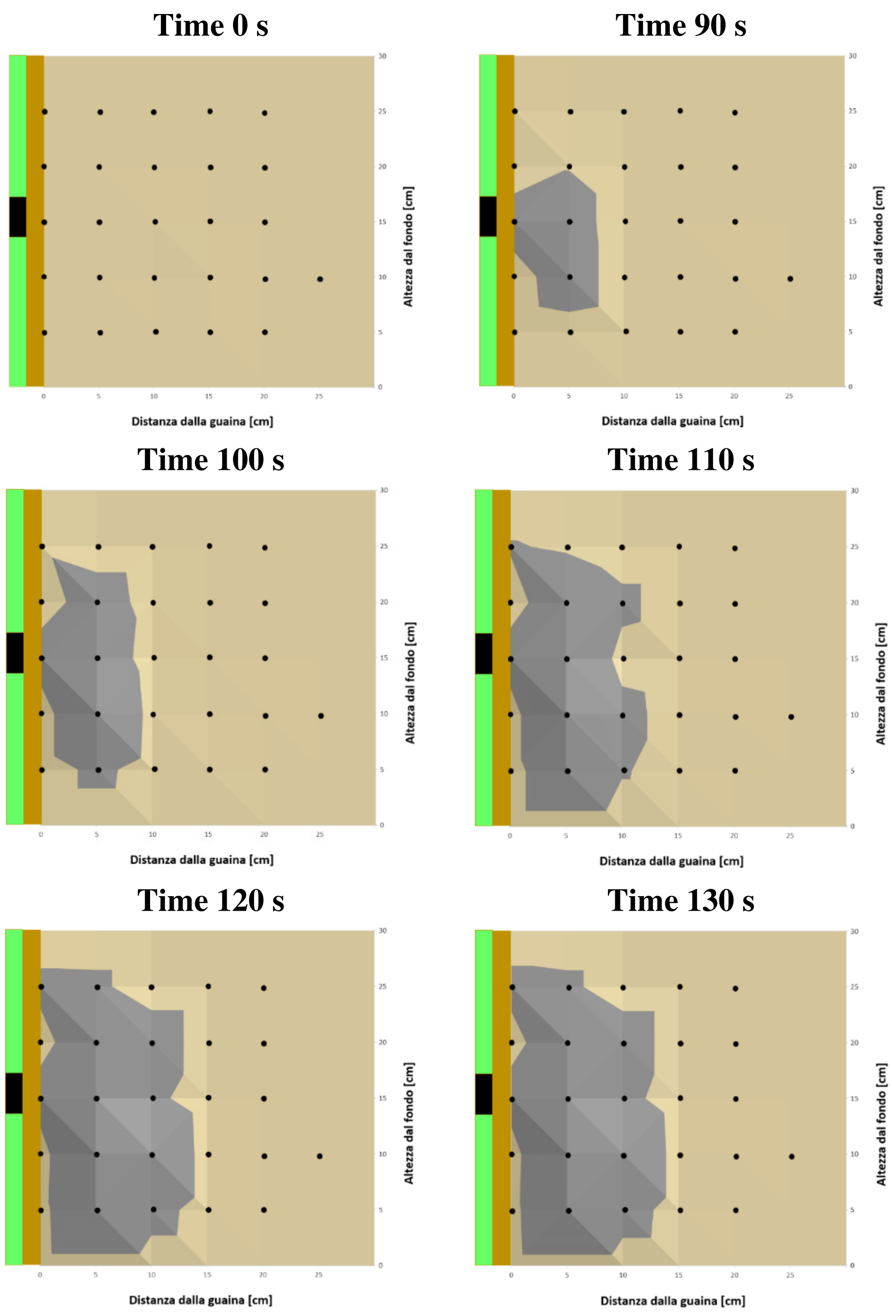


Figure 39: propagation of the mixture in the soil sample during the cement mixture injection #5

Consolidated soil bulb

The treated soil is left to mature, and the bulb of consolidated material is obtained.

The volume of the bulb is determined by carrying out a photogrammetric survey and a terrestrial laser scanner survey.

To carry out the photogrammetric survey, 92 photographs of the bulb were taken, with the help of Agisoft software the 3D model was created and the bulb volume of 24.8 liters was calculated.

For the laser scanner survey, six measurements were taken, the 3D model was created using Agisoft software, and the volume of the bulb was calculated to be 24.4 litres.

Figure 40: cemented soil bulb

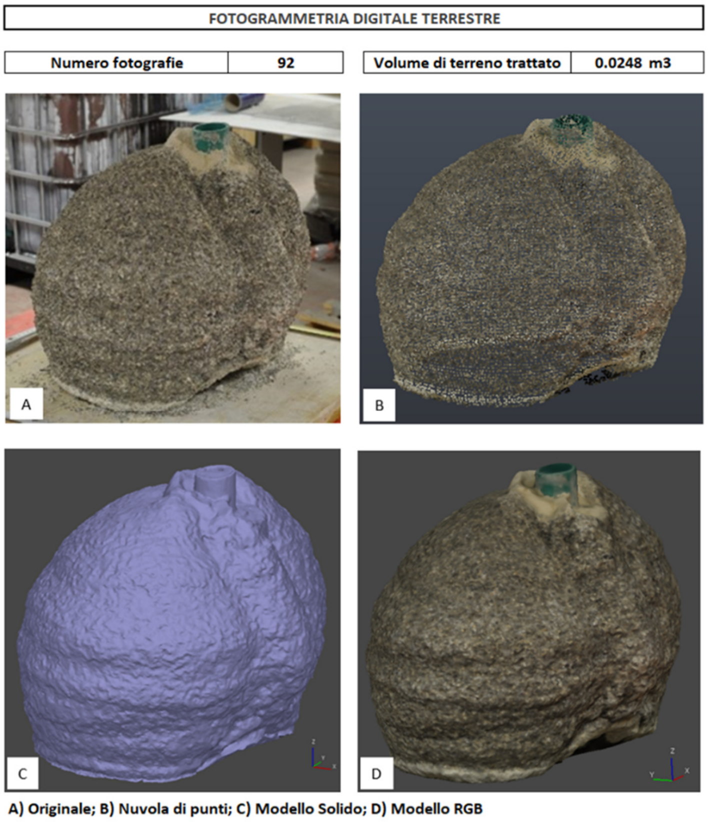


Figure 41: results of the photogrammetry performed on the treated soil block of the test cement mixture injection #5

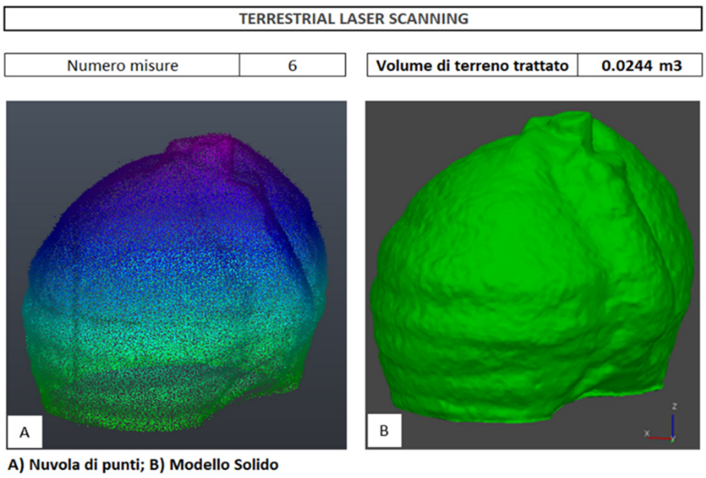


Figure 42: result of TLS survey

5.2.9 Multiple mixture injections

Test carried out using the cylindrical machinery, the sheath has filled the annular gap, the cement mixture was injected into the ground using the sleeve tube in the first pass. Two injections of the silicate mixture were subsequently carried out, 7 and 8 days after the injection of the cement mixture.

A piston injector was used for pumping the mixture, as per in situ injections. The double packer was used.

The mechanical seal between the TAM and the cover is given by a metal flange that contains the pipe and inside which the bentonite sheath is thrown to prevent the passage of mixture between pipe and sheath. The flange is fixed to the cover by means of threaded rods and bolts.

Within the cylindrical apparatus, 195 kg of granular material was compacted into a volume of 120 litres, for a density of 1.61 kg/l.

Silicate mixture

Mix design of the silicate mixture and its rheological characteristics are shown in the table below. Silcon 3090, a single-component preparation is used for the packaging of the mixture.

During the injection phase, 30 liters of mixture are injected in two stages, 20 liters in one injection and 10 liters in the other.

Confezionamento miscela inj
Utilizzo iniettore

Materiale	Massa [kg]
Acqua	47
SILCON	20
R a/s	2,35

Temperature		
T aria	17,5	[°C]
T H_2O	16,5	[°C]
T misc	32	[°C]

Cono di marsh		
0 min	30	s
10 min	31,4	s
20 min	-	s

Setting time	26	min

Table 1: silicate mixture mix design and rheological characteristics.

Thermocouples

The 8 thermocouples placed inside the soil sample are arranged at 3 heights with respect to the bottom (5, 15 and 22.5 cm) and at different radial distances from the sheath (5, 10, 15 cm), they are all contained within the same plane, the position of each thermocouple is indicated in the table below. The acquisition of signals is carried out using the Bleb system.

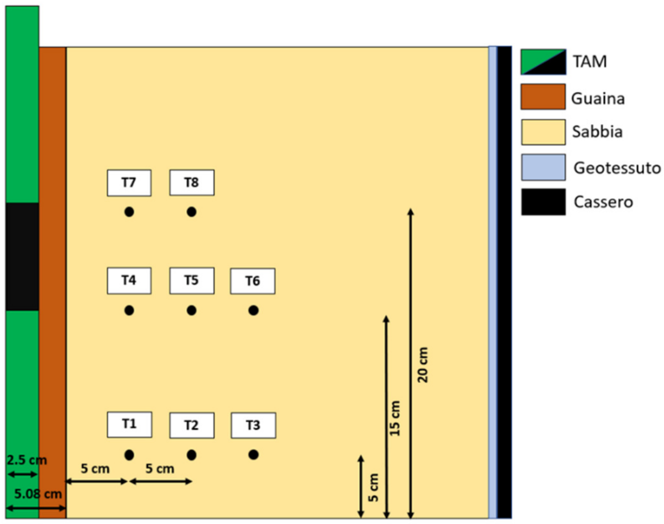


Figure 43: position of thermocouples in the soil sample

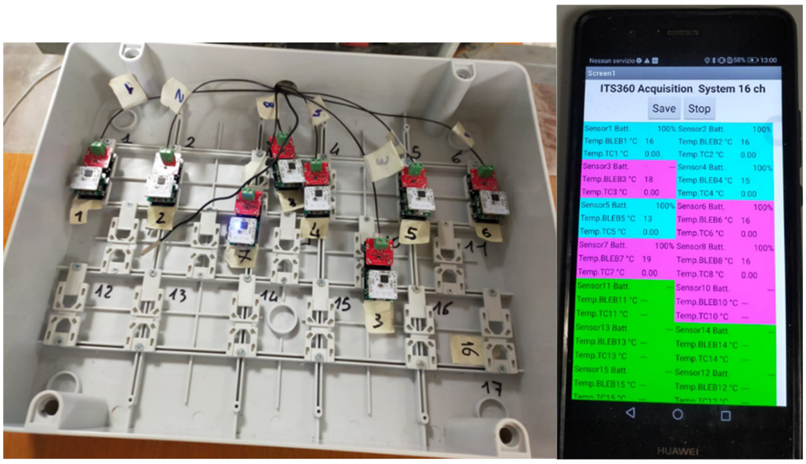


Figure 44: Bleb system (on the left), smartphone with acquisition App (on the right)

Results

The injection parameters: injected volume, pressure and flow rate are recorded by the injector for all three consolidating injections.

The temperature variation recordings, carried out using thermocouples and the Bleb system, recorded only the passage of the first injection of the mixture, this is due to the fact that the thermocouples remained incorporated in a portion of cemented and non-cemented ground. were lapped by the subsequent injections of the silicate mixture.

Cement mixture injection (1° stage)

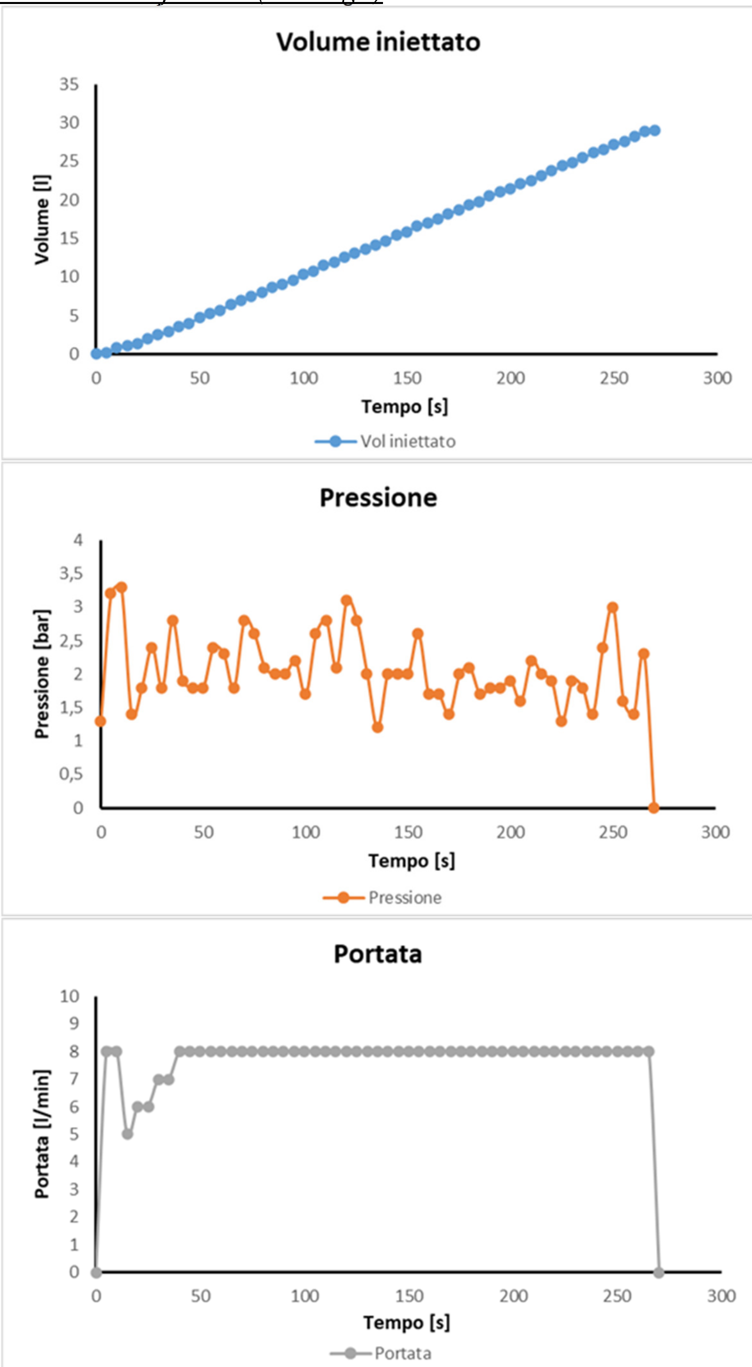


Figure 45: trends of volume, pressure, and flow rate over time

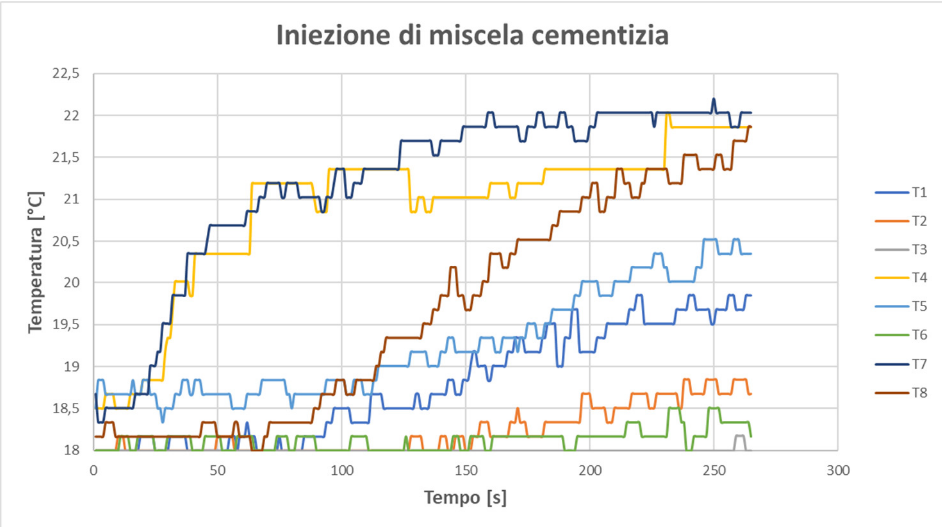


Figure 46: trend of temperature over time

	h[cm]	r[cm]	t [s]
T1	5	5	85
T2	5	10	128
T3	5	15	
T4	15	5	15
T5	15	10	95
T6	15	15	215
T7	20	5	17
T8	20	10	90

Figure 47: thermocouples position and time of arrivals

All the thermocouples, except for T3 which appears non-functional and fixed at the value 0, register a voltage variation which is proportional to the temperature variation and therefore to the mixing passage.

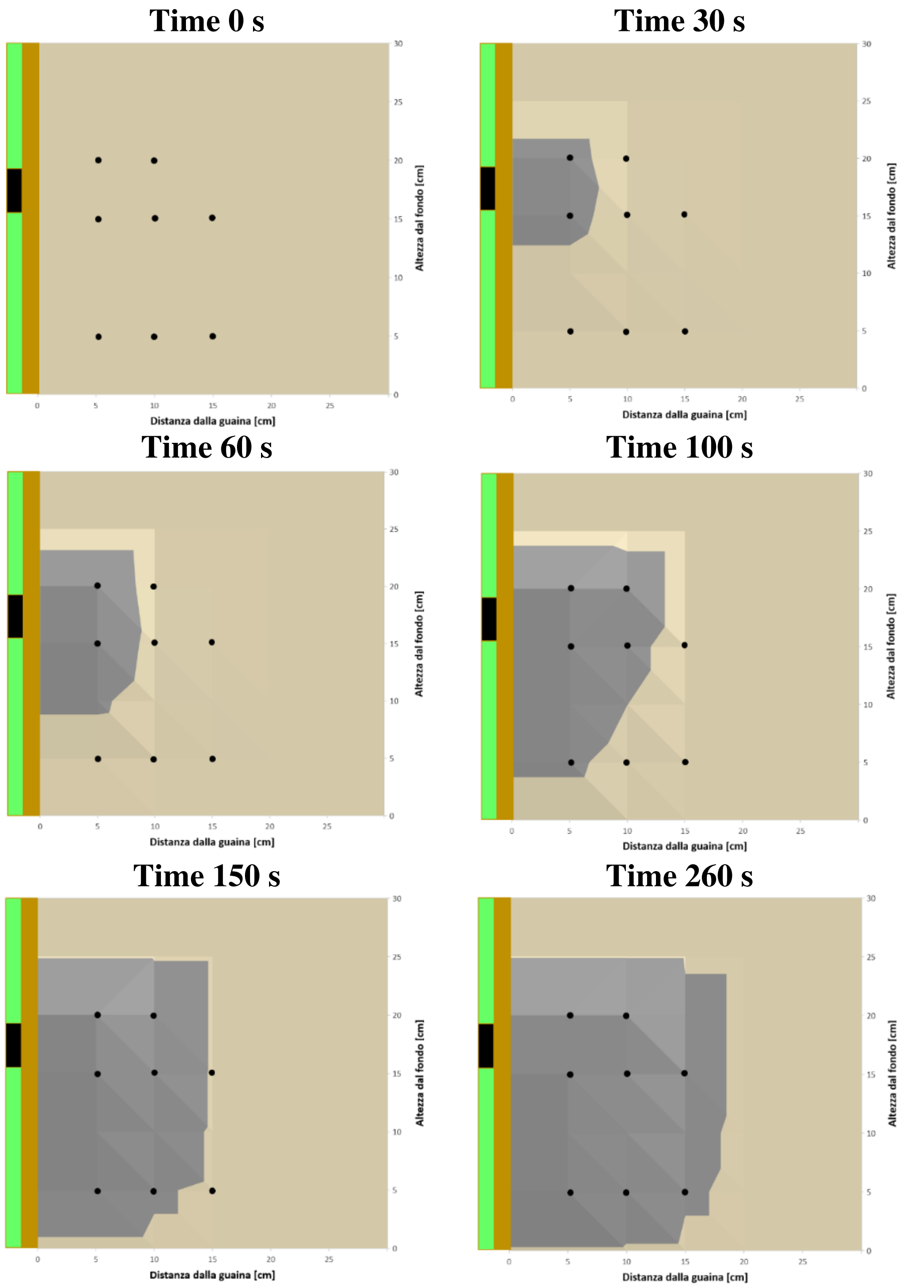


Figure 48: propagation of the mixture in the soil sample during the injection

The following is the trend over time of the injection parameters during the three injections.

First silicate mixture injection:

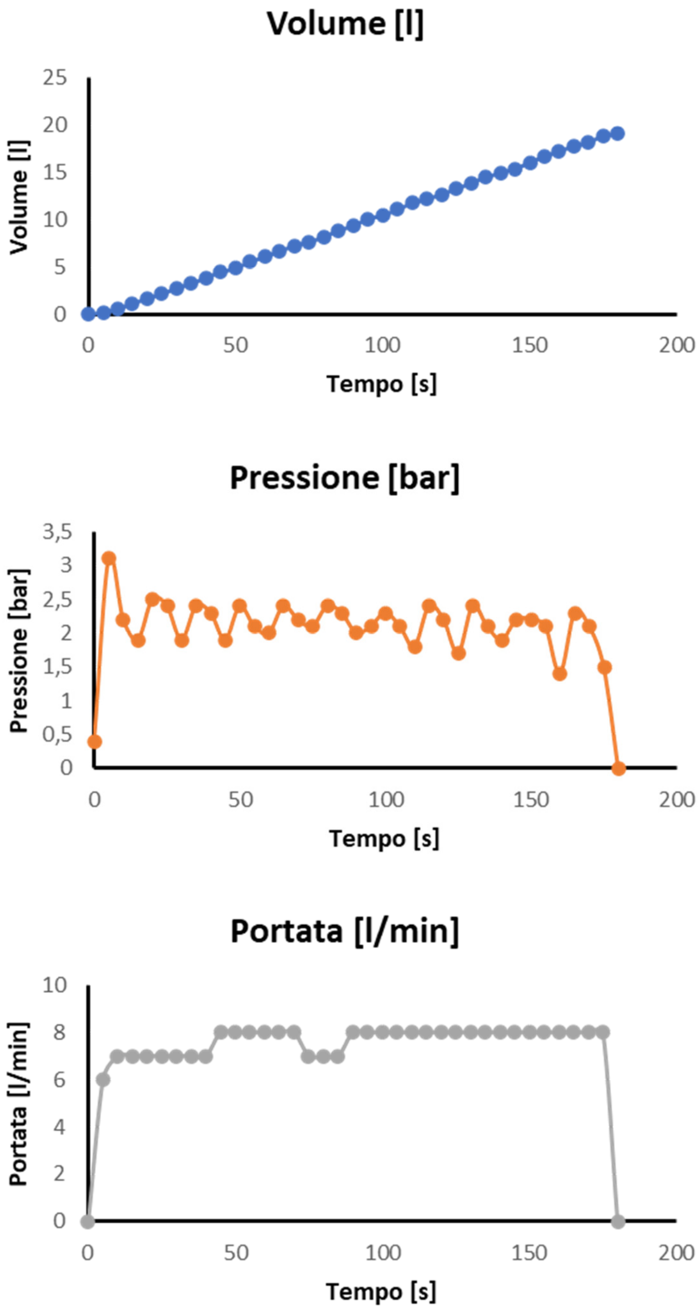


Figure 49: trends of volume, pressure, and flow rate over time

Second silicate mixture injection:

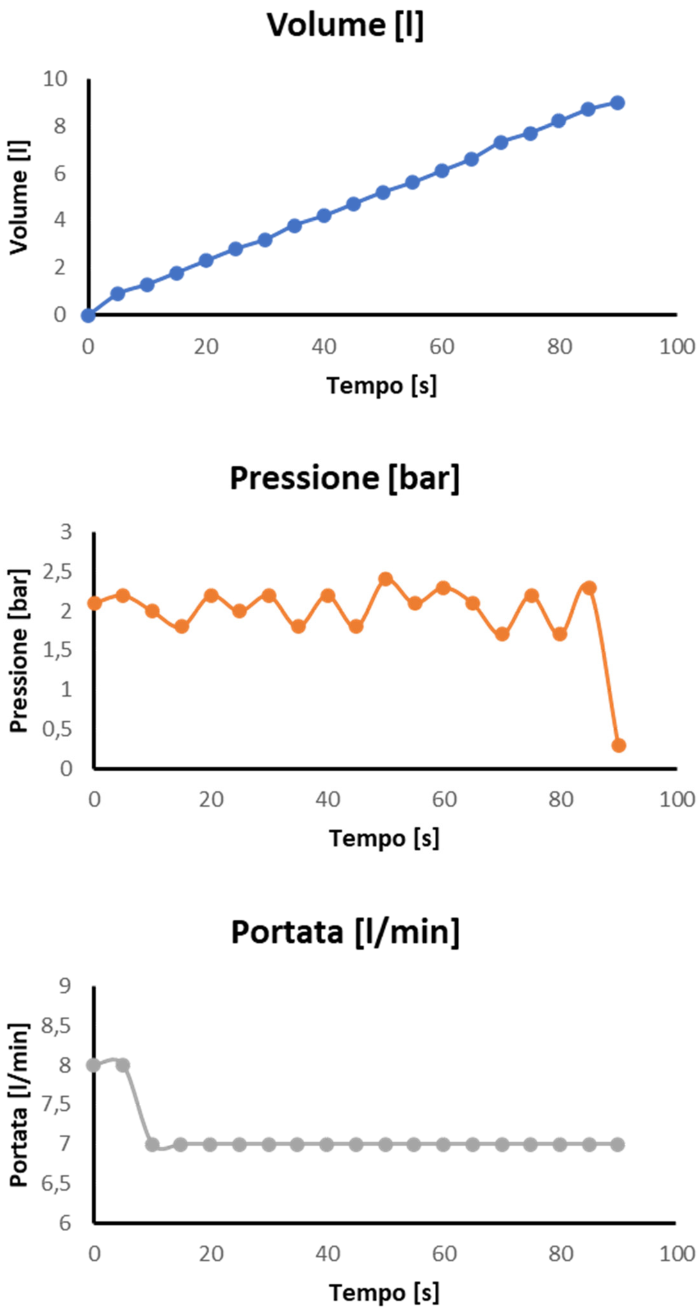


Figure 50: trends of volume, pressure, and flow rate over time

Consolidated soil bulb

The treated soil is left to mature, and the bulb of consolidated material is obtained. The volume of the bulb is determined by carrying out a photogrammetric survey and a terrestrial laser scanner survey.

To carry out the photogrammetric survey, 83 photographs of the bulb were taken, with the help of Agisoft software the 3D model was created and the bulb volume of 126 litres was calculated.

For the laser scanner survey, five measurements were taken, the 3D model was created using Agisoft software, and the volume of the bulb was calculated to be 127 litres.

Figure 51: consolidate soil

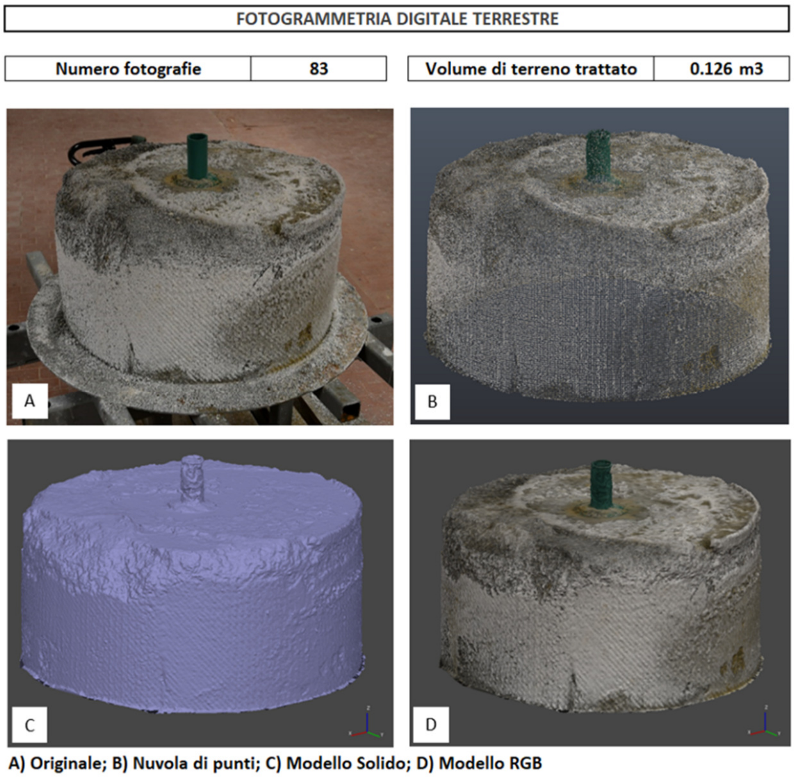


Figure 52: results of the photogrammetry performed on the treated soil block of the test cement mixture injected during Multi injection test.

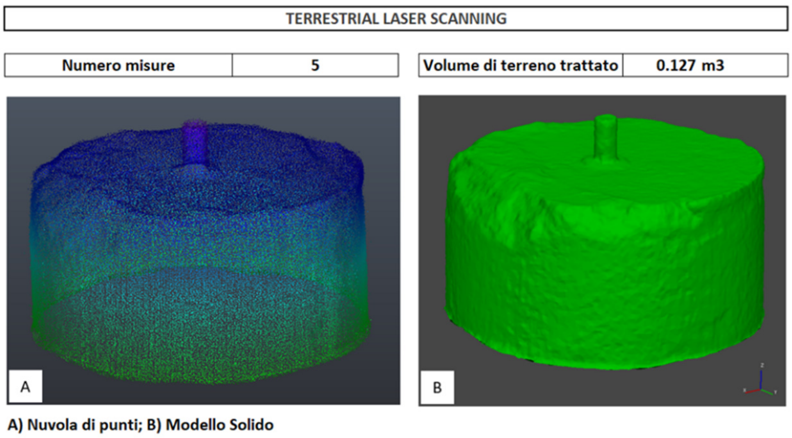


Figure 53: result of TLS survey

5.3 Conclusions

Injections made into sandy soil using the cylindrical apparatus showed that the soil is permeated radially with respect to the valve. The shape of the treated soil bulbs is symmetrical with respect to the axis of the valve tube used for injection.

This type of three-dimensional injection produces a volume of treated soil, geometrically like those obtained by Perret (2000).

The equipment is suitable for testing and allows the same soil sample to be injected one or more times, resulting in treated material that can then be taken and subjected to mechanical, hydraulic, and environmental tests.

Recording and analysing the data obtained during the conduct of the injection tests made it possible to compare the tests, in which, it should be recalled, the same granular material is always used as the test medium, and the same mix design is always used to package the cementitious-based consolidating mixture.

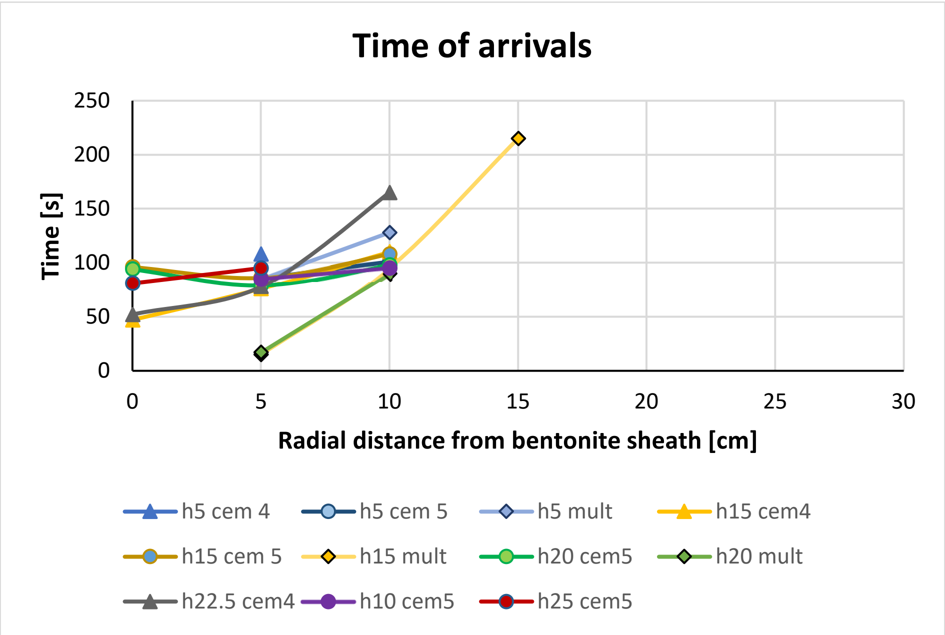


Figure 54: time of arrival of mixture in different injection tests

In the above graph it is possible to visualize the arrival times of the mixture front, for different injections of ternary mixture, at different radial distances from the bentonite sheath. A difference in the arrival times is observed at zero cm distance, varying between 50 seconds at heights of 15 and 22.5 cm, i.e., at the edges of the rubber valve from which the mixture exits, and about 90 seconds, for thermocouples placed at heights of 20 and 25 cm. As for the zero radial distance thermocouples placed at heights of 5 cm and 10 cm, the passage of the mixture is not recorded; this is due to the fact that these thermocouples remained cemented into the bentonite sheath, and the sheath insulated these thermocouples from their surroundings, preventing contact with the cement mixture.

At 5 cm from the bentonite sheath, the arrival of the mixture is recorded after about 86 seconds, at 10 cm the average time of arrival of the mixture is 100 seconds, ranging from a minimum of 90 to a maximum of 165 seconds.

Comparing the volumes of consolidated soil, it can be seen that the bulb obtained from the injection of 30 litres of cement mixture, half the volume of the voids within the soil, has a volume of 67 litres.

The volume of the bulb obtained after the three injection stages, a total of 60 litres of mixture, the total volume of the voids within the soil, has a volume of approximately 127 litres. Twice the total volume of mixture injected returned a twice the volume of cemented soil bulb.

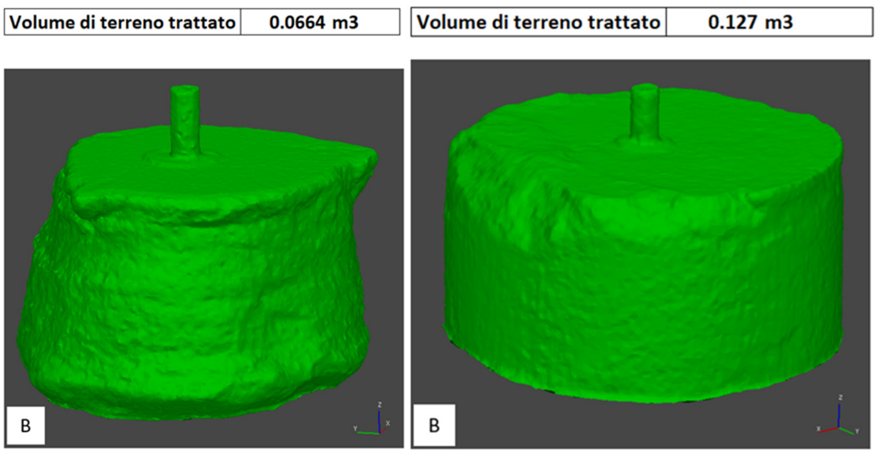


Figure 55: comparison of two bulbs of consolidated soil, the soil sample on the right was injected with twice the volume of mixture and the bulb has twice the volume of the one on the left.

References Chapter 5

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Chapter 6

Comparison between experimental data and data obtained from an analytical model

6.1 Introduction

The most widely used permeation grouting technique for improving soil characteristics is the tube-a-manchettes technique (Warner, 2004), presented in the previous chapters. In this technique, the soil structure does not have to be substantially changed and therefore the injection pressure of the consolidating mixtures is continuously monitored and kept below a certain threshold (Han, 2015). In the works of Gallagher et al. (2007) and Packer et al. (2018), a maximum value is set for the injection pressure, in agreement with this maximum value is the formula of Park and Oh (2018) which defines the injection pressure as 15kPa/m×d, where d is the depth treated.

As reported in the works of Kim J. S. et al. (2009) and Boschi et al. (2023) and witnessed by various experimental evidence, the geometry of the consolidated soil can be assimilated to a series of spheres around the valves present on each valve pipe.

During the design phase of the consolidation intervention by means of permeation grouting, it is fundamental to relate the distance travelled by the grout in the ground with the operating parameters represented by the flow rate, imposed, and the consequent injection pressure. Knowing the distance travelled in fact makes it possible to design the intervention from a geometric point of view, rationalising the number, position, and arrangement of the holes in which the grouted pipes are placed.

At present, most of the data on soil permeation treatments are experimental and come from work carried out in situ, characterised by a particular soil and a particular grout. Therefore, the design phase of the intervention is mainly carried out experimentally through large and expensive in-situ tests.

From a theoretical point of view, there are few models in the literature to simulate soil injections, the first ones presented are those of Raffle and Greenwood (1961) and Tomiolo (1982), who assumed that the convective phenomenon is dominant and that the flow of grout is governed by the standard Darcy's law.

A more systematic analysis of the complex chemical-physical interactions that occur between the different phases during grout injection has been conducted numerically by Bouchelaghem et al. (2001), this model starts from a complete mathematical description of the filtration-advection-dispersion process that occurs in miscible grouts propagating in saturated deformable porous media, but its use is often hampered by the difficulty in obtaining the constituent parameters of the model.

A simpler application model was presented in the work of Boschi et al. 'Permeation grouting in soils: numerical discussion of a simplified analytical approach'. The input data of the model are the rheological characteristics of the mixture, the particle size characteristics of the soil, the injection parameters (primarily the flow rate) and the geometry of the manchettes and the bentonite liner.

In this chapter, the model will be validated by comparing the analytical results with the data obtained during the tests.

6.2 Simplified analitical model

For these reasons, it is decided to compare one of the tests previously carried out with the cylindrical apparatus with the model reported in the work of Boschi et al. (2023), in which the authors proposed a simplified analytical model for 1D spherical geometry. This model is based on the assumptions already introduced by Raffle and Greenwood (1961) and Coskun and Tokdemir (2020) and on the assumption that any pressure drop occurs in the ground.

This model aims to predict the temporal evolution of the progress of the mixture front and the pressure at the injection point, these quantities are related to each other by means of Darcy's law and the grout mass conservation equation, a constant flow rate Q being imposed.

The solution to this system of equations is obtained by making a series of assumptions:

a) Isotropic and homogeneus soil
b) Grout incompressible, immiscible with interstitial fluids and characterised by time-independent Newtonian rheology.
c) Quasi-static process
d) Flow regime laminar
e) Any chemo-hydro-mechanical coupling disregarded (Bouchelaghem et al., 2001), (Wang et al., 2022)
f) Spherical source and infinite spatial domain
g) head losses concentrated in the injected grout, being more viscous than the interstitial one.
h) Gravity and capillarity negligible

Under these assumptions, the problem becomes 1D and the only spatial variable turns out to be r, the distance from the centre of the spherical source.

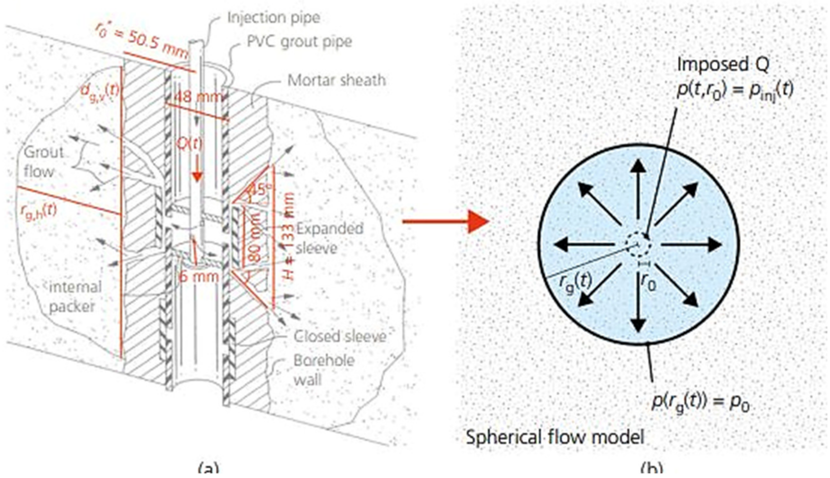

Figure 1: From (a) in situ geometry (source: modified figure taken from www.sindong.com.sg), to (b) numerical model.

The domain completely saturated by the slurry evolves over time, **r** is between **r_0** and **$r_g(t)$**, with **r_0** the radius of the injection source and **$r_g(t)$** the distance reached over time by the mixing front. The solution is obtained by imposing constant Q when **$r = r_0$**, and **$p = p0$** when **$r = r_g(t)$** and integrating the equations in time and space. The equations are thus obtained:

$$R(T) = \frac{r_g(t)}{r_0} = \sqrt[3]{1 + \frac{tQ}{nV_{inj}}} = \sqrt[3]{1+T}$$

$$P(T) = 1 - \frac{1}{R(T)}$$

Where **T** is dimensionless time, **n** is the soil porosity e **V_{inj}** the volume of injection source, $P = (p_{inj} + p_o)/(p_0 P_r)$ and $P_r = Q\mu_g/(A_{inj} r_0 p_0 (k/r_0^2))$, with μ_g is the viscosity of the grout, **A_{inj}** injection source area and **k** the soil intrinsic permeability.

6.3 Numerical analyses

Boschi et al. (2023) used the numerical code COMSOL Multiphysics to solve the problem numerically using the finite element method.

The partial differential equations (PDEs) governing the process (Muskat and Meres, 1936) are the mass conservation equations for each fluid. It is assumed that each fluid obeys Darcy's law and that their coupling is due to capillarity effects. These PDEs are implemented in COMSOL by means of the so-called pressure-saturation formulation, having assumed that all phases completely fill the pore space.

The mesh was made very fine around the injection source and wider in the remaining domain.

For the reference case, the input parameters used are listed in Table 1: A poorly viscous grout, a flow rate Q commonly imposed in practical applications. The injection, set for a duration of 4 minutes (time of injection t_{inj}), it is assumed that it takes place in an approximately monogranular sand and that the grout is characterised by a viscosity of the same order of magnitude as water.

H [m]	0.133	**Q [l/min]**	7
a [m]	0	**ρ_g [kg/m^3]**	1240
n [-]	0.41	**μ_g [Pa s]**	0.006
k [m^2]	8.6×10^{-10}	**p_{ec} [kPa]**	0
m_{vG} [-]	1	**t_{inj} [min]**	4

Table 1: input data of the reference case

6.4 Results

The results of the analytical model proposed by Boschi et al. (2023), which show the evolution of the position of the mixture front over time, are plotted together with the data obtained during the experimental test and compared.

Regarding the experimental data, the distance r from the centre of the injection source was calculated for each point at which the time of the mixture passage was recorded. As far as time is concerned, the time at which the first mixture passage at zero distance from the sheath is recorded was taken as time zero.

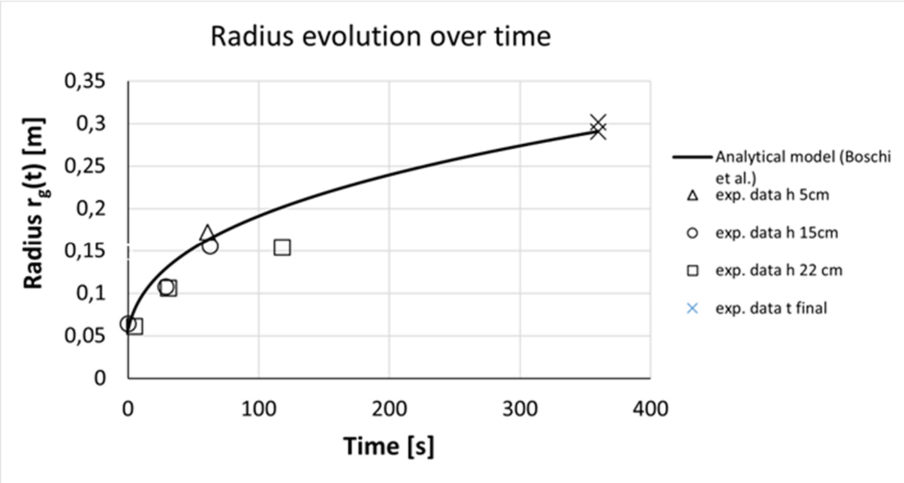

Figure 2: Comparison of experimental data with the analytical model of Boschi et al. (2023)

After verifying the correspondence of the evolution of the penetration radius over time between the model and the experimental tests, it was verified that the progression of the mixture in the soil depends on the injection and is not influenced by gravity and capillarity. The formula proposed in the work of Boschi et al. (2023) is applied:

$$v_{inj}/K_g$$

where v_{inj} is the injection rate calculated as Q_{inj}/A_{inj}, Q_{inj} is the injection rate, A_{inj} is the surface area of the injection source, and K_g is the permeability of the soil to the grout.

- If $v_{inj}/K_g > 2$ the process is not influenced by gravity,
- If $0.03 < v_{inj}/K_g < 2$ the injection pressure drives the process, but gravity is not negligible,
- If $v_{inj}/K_g < 0.03$ the process is governed by gravity.

The ratio of injection velocity to grout permeability is equal to 1.57 and therefore the influence of these two quantities on the propagation of the mixture can be considered almost zero.

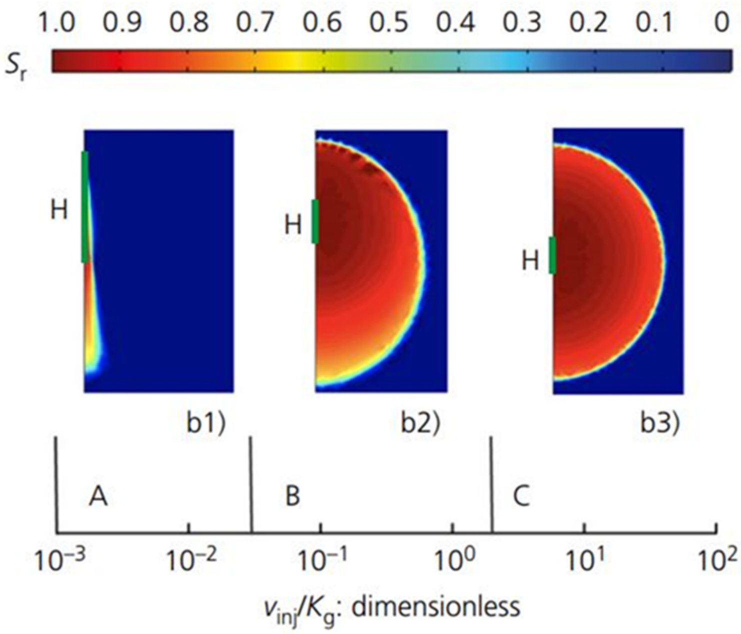

Figure 3: influence of vinj/Kg ratio in the injected grouted area shape after 10 minutes of injection (Boschi et al., 2023)

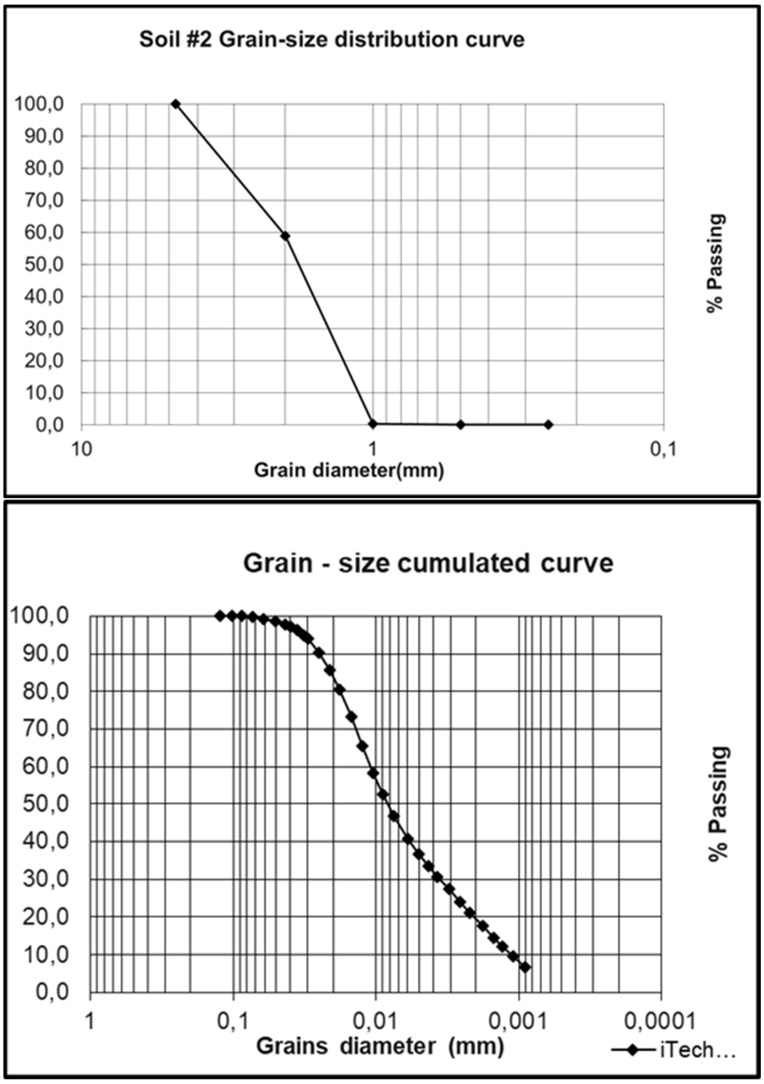

Figure 4: Grain size distribution curve of soil and cement

Finally, it is verified that the solid phase, which makes up the grout, does not restrict injection by forming a barrier called a cake. The formula given in the work of Boschi et al. (2023) is applied:

$$^{1}/_{2}\, d_p > d_{95\ grout}$$

Where $\mathbf{d_{95\ grout}}$ is characteristic cement particle size, $\mathbf{d_p}$ is the maximum value of a particle that can be transported inside of a solid soil matrix as reported by Boschi et al. (2023), citing work by Kenney et al. (1985), and is a function of the characteristic diameters $\mathbf{D_{15}}$ and $\mathbf{D_5}$ and the uniformity coefficient **Cu**.

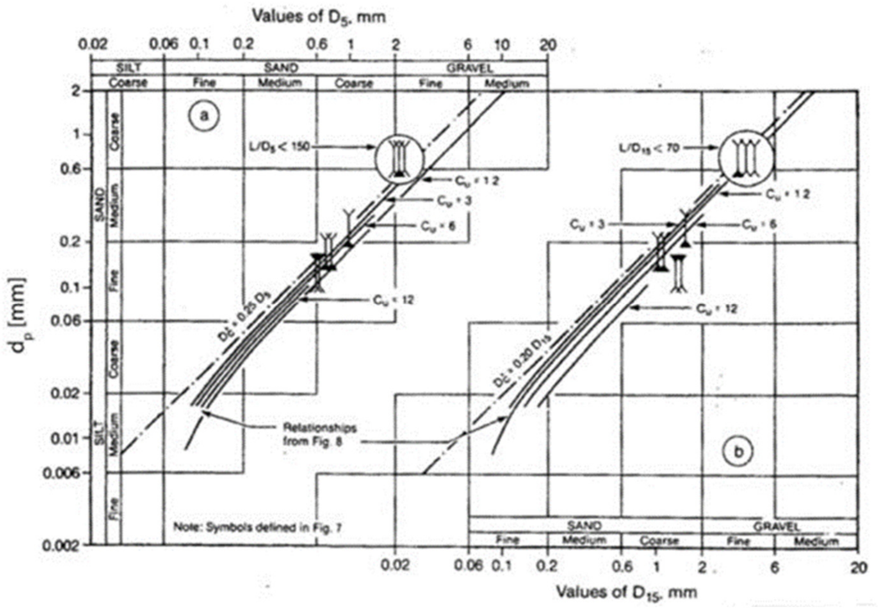

Figure 5: diagram for deriving d_p from values of D5, D15 and Cu (Kenney et al., 1985)

Having obtained the values of D_{15}, D_5 and Cu from the particle size curve of the granular material making up the soil sample and the d_{95} value of the cement, it was verified that the solid phase does not form a barrier by occluding pores and forming 'cakes': $\mathbf{1/_2\, 0.3 > 0.032}$ **.**

6.5 Conclusions

The comparison between the values obtained from the analytical model and the experimental data, recorded during the injection test in the soil sample, allowed the model of Boschi et al. (2023) to be validated.

The experimental data of the advancement of the mixture front, acquired by means of thermocouples, are indeed in agreement with the calculated radius rg(t) values; in agreement with the model is also the measurement of the radius of the cemented soil bulb, obtained following the treatment.

The assumptions on which the model is based are verified, the maximum size of the grout particles is much smaller than the maximum size of a particle that would be able to pass through the solid matrix. The influence of gravity is also very limited, although not completely negligible.

Validation of the model confirms the spherical geometry of the bulb formed around the rubber valves, placed at regular distances along the manchettes.

Figure 6: quasi-spherical cemented soil bulb

As large-scale laboratory tests and predictive models go hand in hand, the importance of these tests for the design of permeation grouting interventions will increase in the future.

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Chapter 7

Technological investigation towards wedge shaped apparatus under pressure

7.1 Introduction

During this thesis work, tests were carried out using a cylindrical apparatus, in which it was possible to carry out mixture injections into the soil. At the same time as these tests, research was carried out into the design, construction, and operation of a wedge-shaped apparatus, to be used for carrying out mixture injections into a soil sample. This apparatus must make it possible to simulate in-situ conditions accurately, especially the soil sample inside it must be subjected to the loads present in a soil under water table.

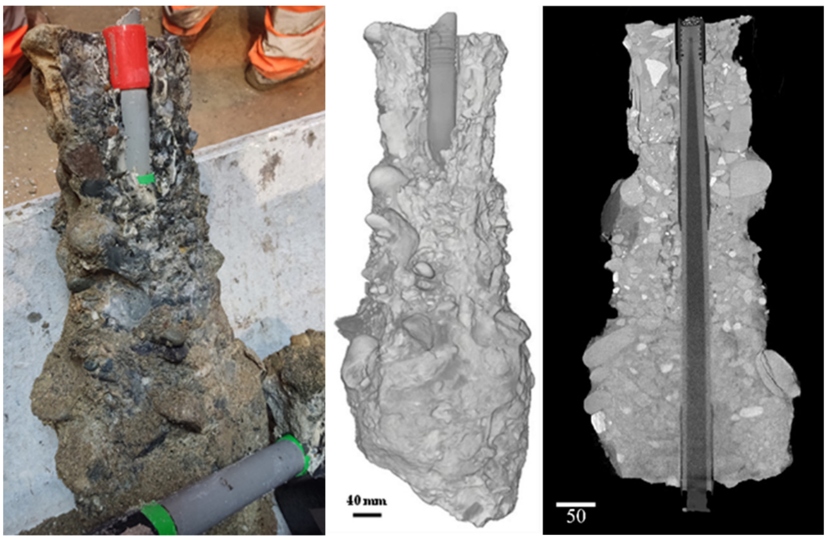
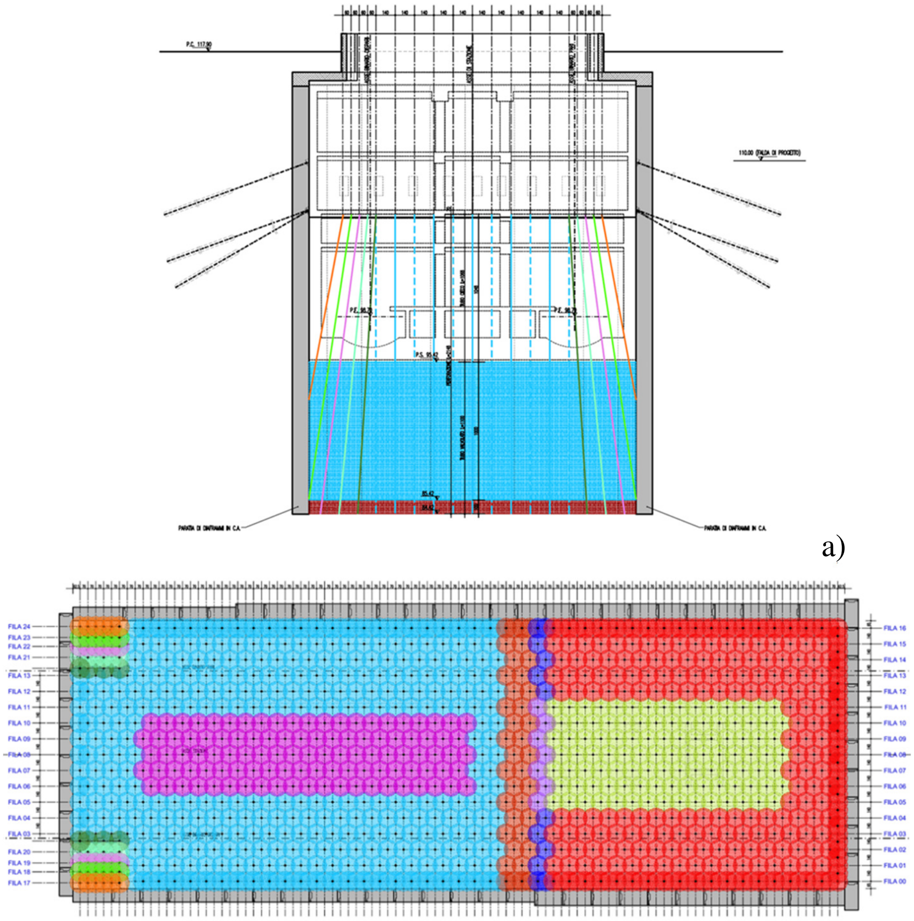


Figure 1: consolidated soil bulb, photo (left), 3D model (centre), section from CT scan (right) from Bastianini thesis (2023).



a)

b)

Figure 2: cross-section (2a) and plan (2b) of a soil consolidation and waterproofing operation using permeation grouting for excavation of ground beneath the water table from Bastianini (2023)

To achieve this goal, it was decided to follow two parallel paths: the first consisted of making modifications to the cylindrical-shaped apparatus presented in the previous chapters, and the second of conducting tests with a smaller, cubic-shaped apparatus.

Given the good experimental results obtained from the injection tests carried out and the good functioning of the cylindrical apparatus presented previously, we proceeded to refine it, so that it is also possible to carry out the saturation of the soil sample and its confinement to the in-situ pressure conditions.

The cube-shaped apparatus, called SquaCol, was conceived, designed, and constructed to study the problem of hydraulic seals at the junction points between three perpendicular planes.

The technical solutions developed in this phase will be used in the future to construct a wedge-shaped apparatus capable of confining the soil inside so that it is subjected to both a vertical load simulating lithostatic loading and a hydrostatic load conferred by pressurising the water saturating the sample.

The advantage of making the apparatus characterised by the wedge shape is the possibility of increasing the permeation radius of the mixture in the soil with a much smaller increase in volumes, of soil and fluid, than in a cylindrical-shaped apparatus.

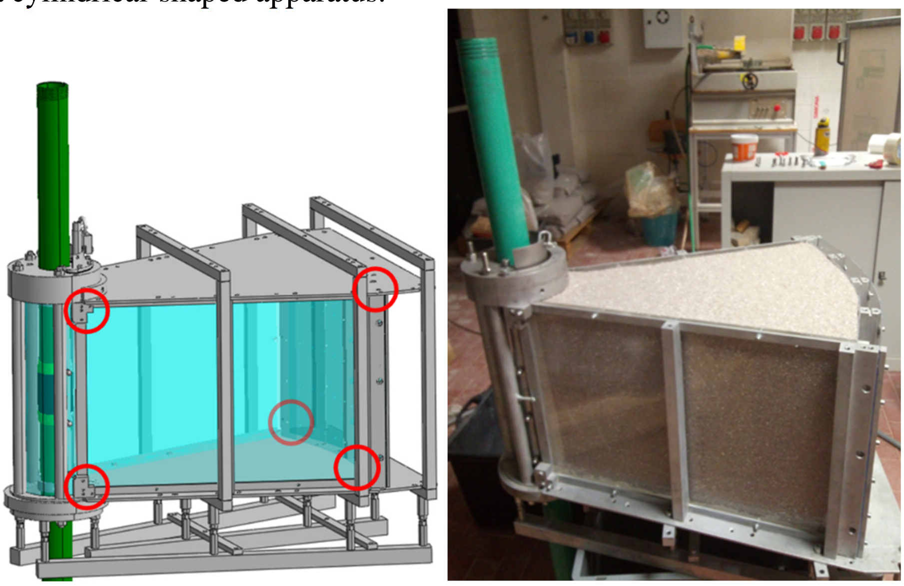


Figure 3: wedge-shaped apparatus, on the left 3D representation with the triple junction points highlighted, on the right photo with soil sample inside.

7.2 Cylindrical apparatus for low pressure saturated soil test

To ensure that the tests are conducted under conditions that are as close as possible to reality in situ, it was decided to make some modifications to the cylindrical structure that had been used to carry out the laboratory injections. The central cylindrical structure was retained, albeit with some minor modifications, while the bottom and lid were changed.

The two elements, which were previously made of steel, are replaced by two wooden panels measuring 1x1 m and 30 mm thick, and to ensure the structural tightness and reduce deformations, U-profile steel bars are placed below the bottom and above the lid, joined together with threaded rods to function as frames.

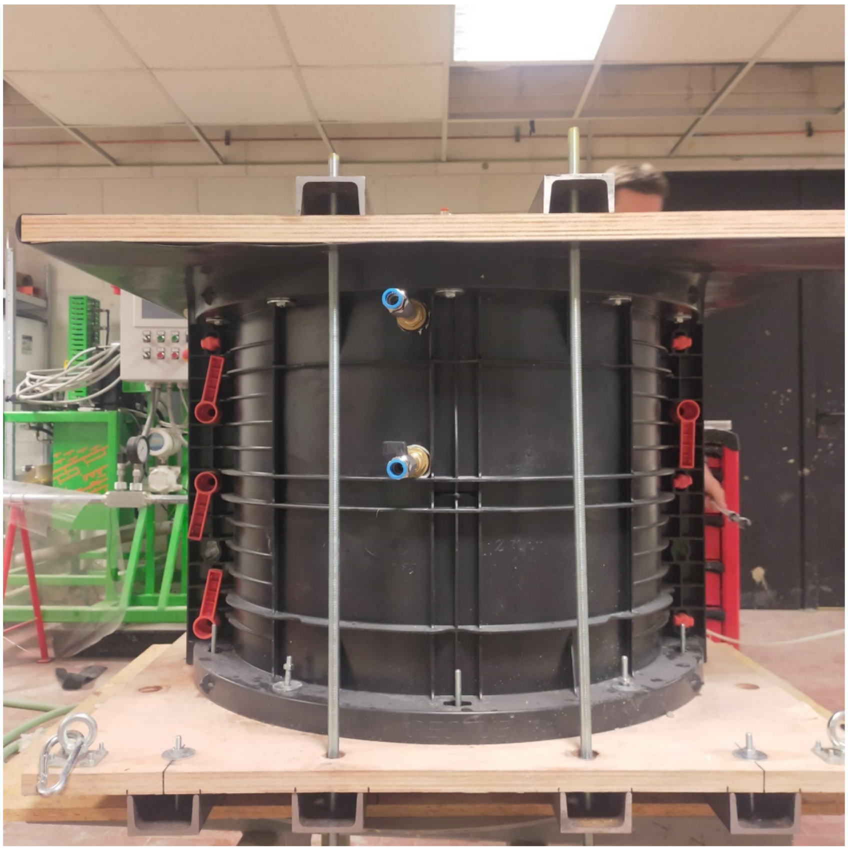


Figure 4: modified cylindrical apparatus with new top and bottom, iron beam and drainage system.

7.2.1 Modified top and bottom

The steel bottom and lid were replaced by two wooden panels, structurally reinforced by steel frames made of U-profiles and threaded rods.

To dimension these elements, 3D finite element modelling was carried out using Fea FX software. A pressure of 100 kPa was imposed on the wooden panel and the deformations were checked, which with the reinforcement of the steel bars was found to be a maximum of 0.3 mm.

The beams chosen are UPN80, the threaded rods are M14, and 30-mm-thick panels were chosen for the wooden panels.

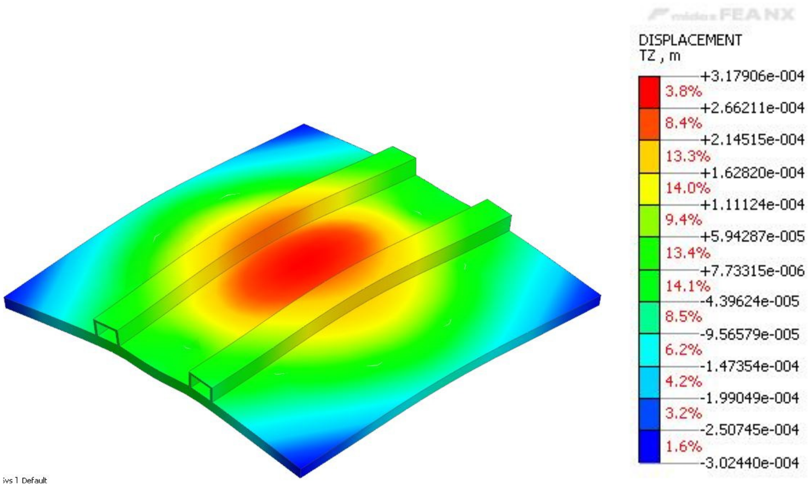


Figure 5: 3D model of the lid and bottom reinforced with steel bars, deformations in the vertical direction due to the application of a pressure of 100 kPa are shown.

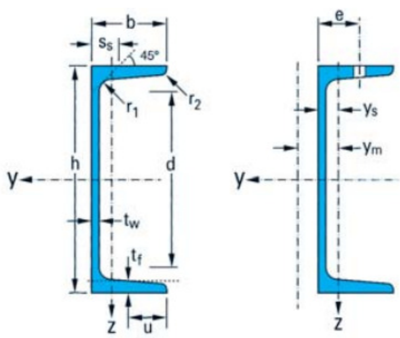


Figure 6: geometry of the UPN80 bar used as structural reinforcement for the cylindrical apparatus closure.

To ensure the hydraulic seal, two 1x1 m rubber sheets, 5 mm thick, are placed between the cylindrical formwork and the wooden panels, acting as gaskets.

In the centre of the cover, an 80-mm-diameter hole is drilled to allow the passage of the TAM. To guarantee the hydraulic seal, a steel anti-loosening flange was mounted around the pipe above the cover. The flange is equipped with a circular rubber seal that expands when compressed and seals the manchettes pipe.

Finally, a hole for the introduction of pressurised air is made on the lid, allowing the rubber sheet to be pressurised, which in this way transmits pressure to the soil sample, simulating lithostatic pressure, since a 10 metres depth (100 kPa).

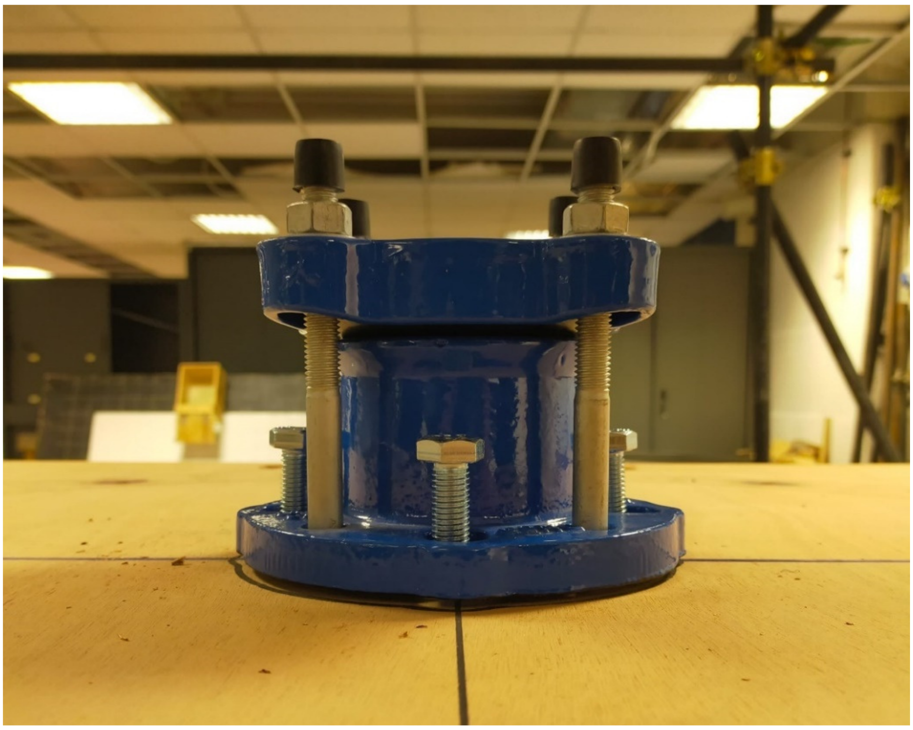


Figure 7: the anti-loosening flange used to guarantee the hydraulic seal between the cover and the valved pipe.

7.2.2 Under pressure drainage and pressure tanks

Circular holes, 26 mm in diameter, were drilled in the cylindrical formwork to allow the installation of wall passages to which threaded pipes are connected. This system makes it possible to connect the inside of the apparatus to pressure tanks that allow the fluids inside the sample to be confined and thus simulate the hydrostatic pressure that is present in situ since 2 metres of column water (20 kPa).

As a second step, the pressure tanks were then built, with a total capacity of 120 litres, which serve to saturate the soil sample, pressurise the water in the sample and finally allow the water displaced by the mixture to drain under pressure during the injection of the cement mixture.

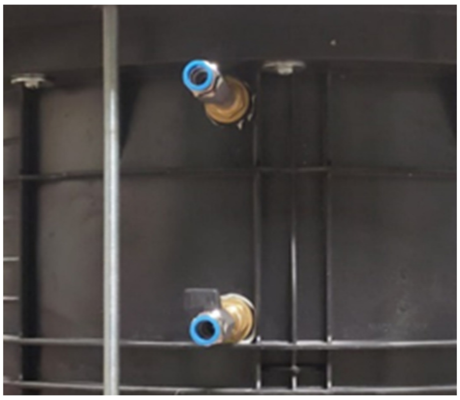


Figure 8: detail of the drains on the cylindrical formwork that allow the water saturating the soil sample to be pressurised and drained during the injection phase.

Prior to constructing the pressure tanks consisting of polycarbonate tubing with an internal diameter of 270 mm and a thickness of 15 mm, a structural strength check was carried out. Considering the tensile strength of polycarbonate to be 60 MPa (Plasting site), Mariotte's formula was applied to verify the tube's resistance to pressure:

$$s = {P_r \times D_i}/{2\sigma}$$

With **s** pipe thickness, $\mathbf{P_r}$ acting pressure, $\mathbf{D_i}$ internal diameter and $\boldsymbol{\sigma}$ tensile strength of the material.

The minimum thickness according to Mariotte's formula, given a maximum pressure of 1 bar, is 2 mm, the thickness being 15 mm, it follows that the structure withstands the imposed pressure.

Figure 9: on the left, the pressure tank built to allow drainage with set pressure, on the right, the detail of the pressurized air inlet, the drainage pipe, and the water supply.

7.3 SquaCol: Cubic apparatus for high pressure test and leak testing at triple junction points

A cube-shaped apparatus called SquaCol was designed and manufactured to solve the problem of hydraulic sealing at triple junction points. The apparatus consists of:

- An aluminium bottom, of dimensions 400x400x20 mm
- An aluminium top, of dimensions 400x400x20 mm
- Two plexiglass side walls, of dimensions 300x300x20 mm
- Two aluminium side walls, of dimensions 340x300x20 mm
- seven frames for apparatus closure, each composed of two steel beams with a box profile 80x50x10 mm and two threaded rows M16.

Figure 10: Cubic injection apparatus called SquaCol.

The side walls have been cut with precision machining to obtain a perfect juxtaposition between them when closing. However, to guarantee the seal of water or air under pressure (5 bar) inside the apparatus, it is necessary to find a material that acts as a gasket.

Initial tests were carried out using rubber profiles as seals, but these were only able to guarantee a seal up to 150 kPa, after which air leakage occurred at the triple junction points.

Therefore, a different sealing system was used, using closed-cell neoprene adhesive strips, commonly used for window insulation. This highly deformable material was able to guarantee a seal up to a pressure of 250 kPa.

However, wanting to reach higher pressures for the confinement of the soil sample, a solution was sought that would allow pressures in the order of 500 kPa. The solution was found by placing on the edges of the walls, in addition to the neoprene adhesive strip, two small strips of mastic of the type used as insulation for sinks.

Figure 11: maximum pressure reached inside SquaCol; the hydraulic seal has been checked.

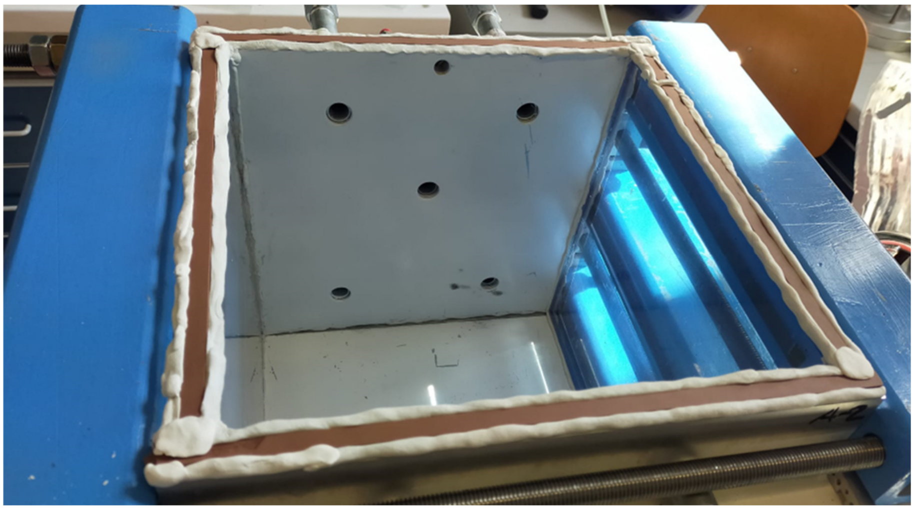


Figure 12: materials used as a gasket between the constituent parts of the SquaCol.

The apparatus, despite its cubic shape, is similar conceptually to an injection column. On the aluminium side walls, arranged frontally to each other, there are threaded holes to connect the apparatus to the pressure vessels that contain the saturation water and the consolidating mixture. The flow of mixture, and of water displaced by the mixture, within SquaCol is one-way. To inject the mixture into the soil sample, the pressure of the mixture must be greater than the pressure of the saturation water.

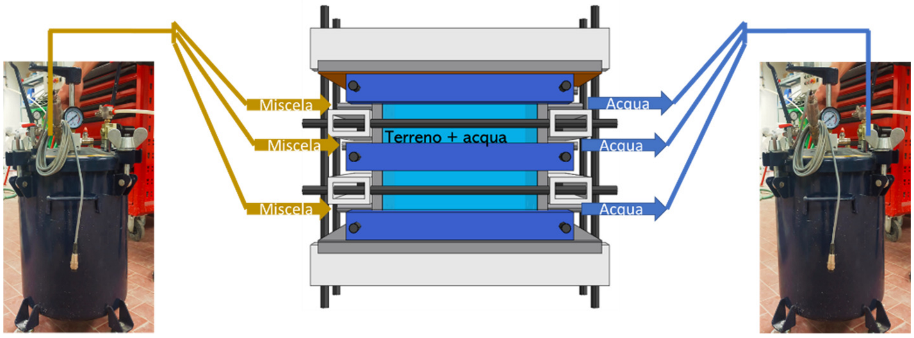


Figure 13: Conceptual scheme of injection with pressure drains using SquaCol.

7.4 Development of a new wedge - shaped apparatus

Thanks to the innovations made to the cylindrical apparatus and the technical solutions applied to SquaCol, it is possible to realise a wedge shape apparatus that is an evolution of a prototype apparatus of the same shape, called ITS 1.0 and with which soil injection tests had already been carried out.

The main advantage of this solution lies in the fact that it is possible to have a soil sample with a large radius, going from the injection point to the back wall, while maintaining a sample with a small total volume. In this way, it will be possible to investigate the maximum radius of penetration of a mixture into the soil and its velocity trend over time, using a sample of similar volume to that contained in the cylindrical apparatus.

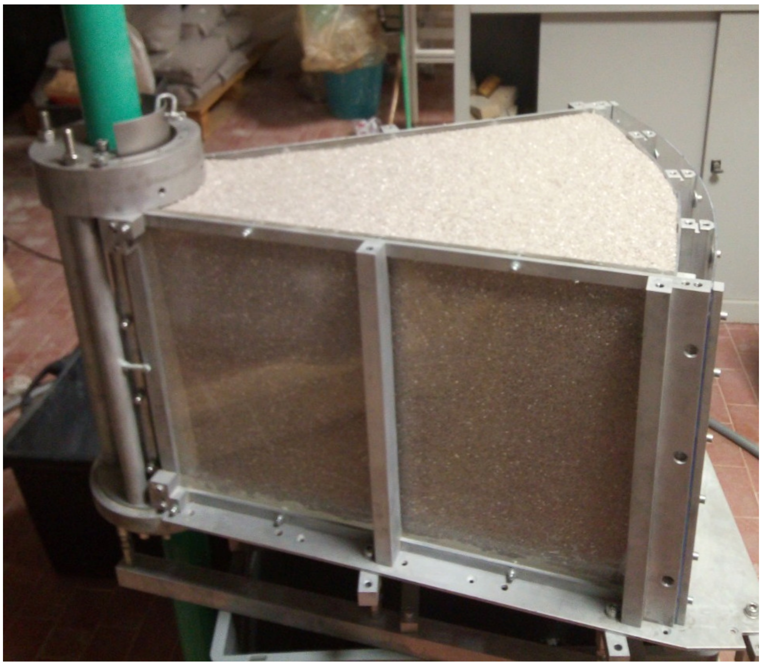


Figure 14: wedge shaped apparatus ITS 1.0, inside the apparatus soil sample ready to inject can be seen.

Using ITS 1.0, injection tests were carried out by using a valved tube, the bentonite sheath was present around the TAM and through fenestrated walls it was possible to see in real time the progress of the mixture front within the soil sample.

This apparatus had been designed and constructed for injection into dry soil, the hydraulic seals at the triple points were not guaranteed. By means of a few tricks, it was possible to saturate the soil sample without detecting water leaks, but then proceeding with the injection of the mixture under pressure, this first caused water and then mixture to leak from the numerous triple points in the structure.

Figure 15: detail of injection test carried out with ITS 1.0, the progress of the mix in the soil and the losses at the triple points can be seen.

7.4.1 Wedge shaped prototype

A prototype wedge-shaped apparatus was constructed using polycarbonate sheets and a polycarbonate cylinder. This apparatus was used to evaluate the possibility of injecting with a manchette tube, and with the presence of a ring of bentonite sheathing, inside a 90° wide wedge of soil. This structure is small, with a maximum radius of 35 cm from the injection source.

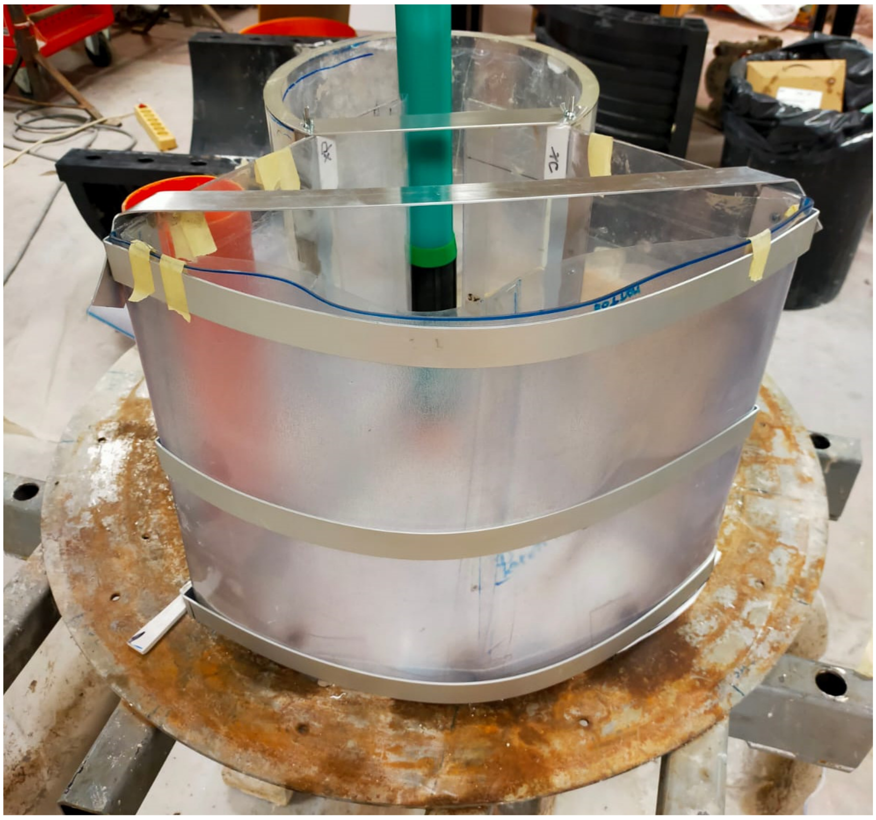


Figure 16: prototype of wedge-shaped apparatus

Figure 17: prototype filled with sand.

The TAM and borehole support pipe are placed inside the apparatus, a drain made of expanded clay is placed, and finally soil is placed inside the apparatus.

It is closed at the top with a PVC sheet and the bentonite sheath is poured.

When the sheath had hardened sufficiently, injection was carried out using the piston injector. Although the structure was not very strong and did not guarantee a sufficient hydraulic seal, a small bulb of treated soil was still seen forming at the end of the test.

Figure 18: mixture leakage from the top of prototype

Figure 19: bulb of soil after cement mixture injection

7.5 Conclusions

With the new technical solutions developed in the tests with SquaCol and the cylindrical apparatus, it will be possible to realise an updated version of ITS 1.0, which will eliminate mixture losses at the triple junction points and guarantee hydraulic and mechanical tightness. The sample inside will be subjected to loads and pressures that will simulate an in-situ soil sample up to a maximum depth of 50 metres from ground level.

Together with the modelling of the phenomenon, this apparatus will be an increasingly effective support for the design of in-situ works and will have the undeniable advantage of operating under different pressure conditions, depending on the depth of the intervention to be simulated.

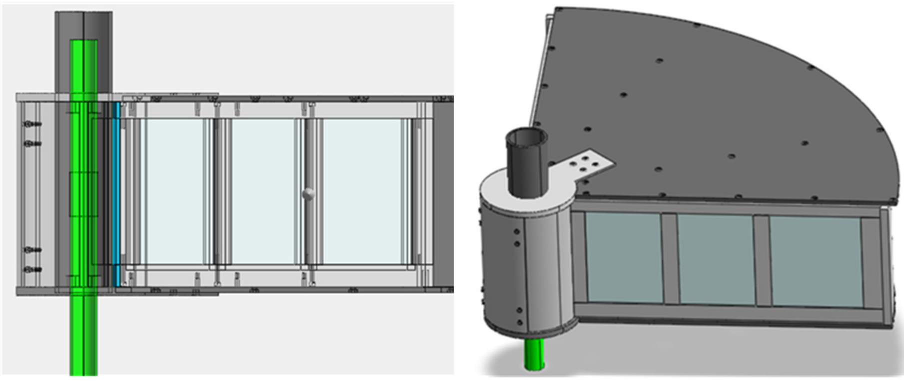


Figure 20: a first version of apparatus wedge shaped with a reinforced structure, section view on the left and 3D rendering on the right.

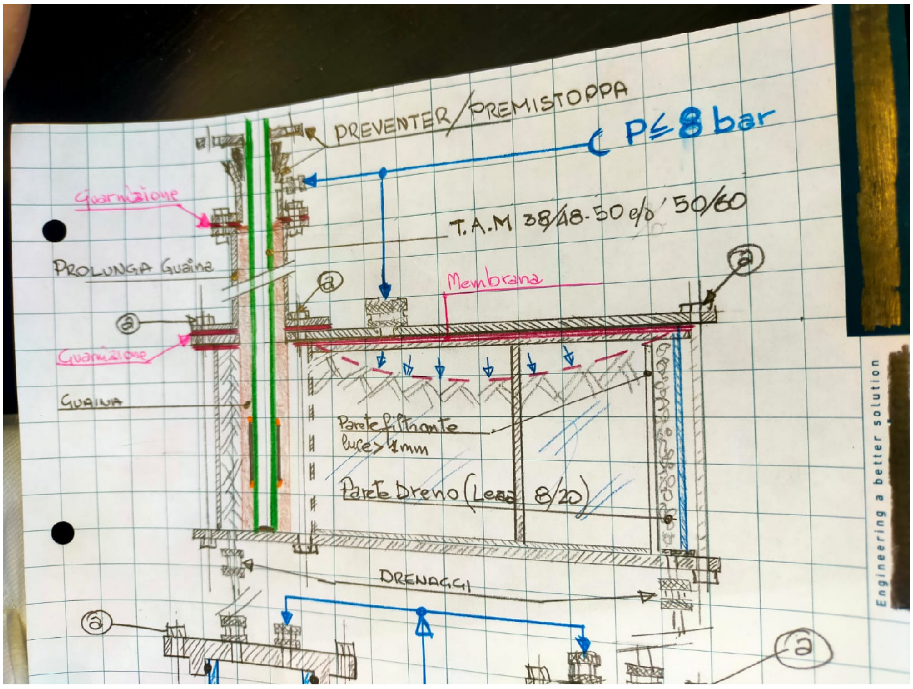


Figure 21: a later version of the apparatus, the presence of the anti-loosening flange can be seen here and drainage pressure tanks.

References Chapter 7

Bastianini G. (2023). Studio dei terreni consolidati con permeation grouting: analisi microstrutturale, geochimica e geomeccanica.

Plasting srl site
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