

A calibration chamber apparatus for grout injection testing

Giada Bastianini¹⁻³, Matteo Ciantia¹⁻², Riccardo Castellanza¹⁻³

1 - Università degli Studi di Milano-Bicocca, Dipartimento di Scienze dell'Ambiente e della Terra, Milan, Italy

2 - University of Dundee, School of Science and Engineering, Dundee, United Kingdom

3 - GroutFreeZLab s.r.l.; Via Corridoni, 11, 20122, Milan, Italy, giada.bastianini@gf-lab.eu

Katia Boschi

Politecnico di Milano, Milan, Italy

ABSTRACT: Permeation grouting is a soil improvement technique widely used in geotechnical engineering to enhance the mechanical properties of soils. The method is based on the injection of consolidating mixtures of various types, which permeate throughout the soil porous matrix, leading to increased strength and stiffness. Studying the process both from the injection perspective and in terms of its effects on the soil is therefore of great importance. The effectiveness and practicability of permeation grouting are assessed in situ by means of field-testing campaigns. However, these field tests present several limitations, including high costs, limited process control, and the inability to directly observe the effects of injection on the soil structure. This research proposes an alternative laboratory-based technology that enables the study of permeation grouting under controlled conditions. The approach involves the design and construction of a calibration chamber capable of reproducing realistic injection scenarios and simulating field conditions.

KEYWORDS: permeation grouting, injections, calibration chamber, physical model, laboratory testing.

1 INTRODUCTION

Permeation grouting is a ground improvement technique that enhances soil resistance and stiffness or reduces its permeability (Arroyo *et al.*, 2012; Chang *et al.*, 2016). It is a technique that involves the injection of grout to fill cracks, joints, or other small defects in rock, concrete, or within the pore spaces of soils and other porous materials. The primary objective is to fill the existing voids with consolidating mixtures injected at low pressure to avoid any displacement of the surrounding material or altering the geometry or volume of the void structure. This method is typically employed to enhance the mechanical properties of the material to be treated and to create impermeable barriers reducing permeability (Warner *et al.*, 2004). There is extensive knowledge of the equipment and procedures involved prior to grout injection. The most used technique is the use of tubes-à-manchettes (TAM), but there is still no standardized and reliable method to verify the effectiveness of the injection.

This uncertainty, concerning the actual extent of grout spread, the achieved mechanical improvements, and the potential presence of untreated zones or defects, poses significant challenges during the design phase (Flora *et al.*, 2012; Boschi *et al.*, 2020). There is only one standard laboratory test—the column injection test (ASTM D4320)—that makes it possible to evaluate the injectability of a specific mixture into a specific soil and the mechanical and hydraulic properties of the treated soil. However, it is limited in terms of treated volume, does not allow the use of in-situ equipment (such as the injectors and TAMs), and is inherently a one-dimensional injection process. Consequently, the injection process has increasingly been reproduced at large scale with 3D laboratory tests to verify many aspects related to the injection itself. For example, three-dimensional (3D) injections were performed in 200 L barrels with site-grade tubes to improve the understanding of the mechanisms governing the effectiveness of cement grout injection into partially saturated soils (Perret *et al.*, 2000). Large-scale tests were also carried out to develop and validate a mathematical model describing fluid flow, mixture transport, and ground deformation, using a cylindrical container and a sleeved tube (Bouchelaghem *et al.*, 2002). However, these studies did not reproduce two key site conditions that affect the reproducibility of injection: the use of a valved tube (TAM) and the presence of a bentonitic sheath surrounding it.

To address these gaps and mitigate the uncertainties related to the performance of permeation grouting, this study introduces a novel laboratory apparatus designed to replicate realistic field injection conditions. The paper describes the design and construction of a calibration chamber (CC) that enables full-scale (1:1) grout injections in granular soils, allowing for detailed observation and analysis of the mechanisms governing grout propagation and soil response.

2 CALIBRATION CHAMBER

In this section, the CC developed to perform full-scale 3D injections tests is presented. The CC is designed to impose and control boundary conditions in order to realistically reproduce all the elements that characterise an in-situ injection. Within this device, the casting of a bentonite liner is implemented. Its presence is very important for two reasons. First, it provides structural support to the borehole, preventing collapse under horizontal ground stresses. Second, the liner prevents the injected mixture from flowing back along the manchettes, avoiding the creation of preferential flow paths. This is achieved through the liner's exerted pressure, which depends on its density and the depth of installation.

The system developed is designed to use real on-site equipment, such as a turbomixer, a piston pump to inject the mixture, a double hydraulic packer and a real tubes-à-manchettes (TAM).

2.1 Design of the CC

The cylindrical apparatus (Figure 1) is divided into three main parts: a lower part, which represents its base; the central part, with the cylindrical container where the soil sample is located; and the upper part.

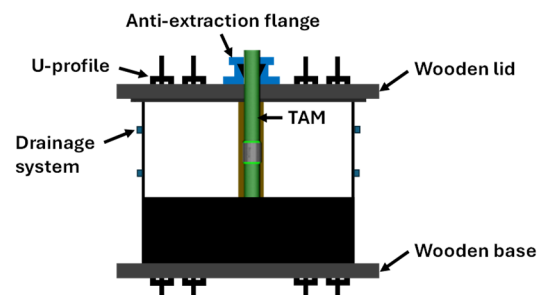


Figure 1. Schematic representation of CC

The bottom part of the CC consists of a base made of a 1 m x 1 m wooden panel, 30 mm thick, treated to minimize the risk of swelling due to water or grout absorption. Two U-shaped steel bars, 10 cm wide and 1 m long, are placed beneath the base, positioned perpendicular to the formwork closure point. These are connected, via threaded rods, to other two U-shaped steel bars placed above the lid, to ensure structural tightness and reduce deformation. The panel contains a total of 14 holes, divided as follows: 10 holes (\varnothing 8 mm) allowing the passage of M8 screws (100 mm long) to attach the panel to the cylindrical formwork; 4 holes (\varnothing 10 mm) for M14 threaded rods approximately 1 m long, used to connect the base panel to the top panel. To prevent water and/or grout leakage during injection, two rubber sheets are placed between the panel and the formwork. A first perforated sheet 90cm x 90cm x 0.5cm is placed on the wooden panel, aligning its holes with those of the panel. To ensure sealing at the soil–confinement interface, an annular rubber gasket 0.2 cm thick is interposed between the lower rim of the cylinder and the first rubber sheet. The gasket is cut to match the annular cross-section of the cylinder wall, with a width equal to (or slightly exceeding) the wall thickness (10–12 cm). This perimeter sealing system provides continuous contact along the entire circumference, thereby preventing leakage of water or mixture during the injection and ensuring mechanical stability of the specimen within the mould.

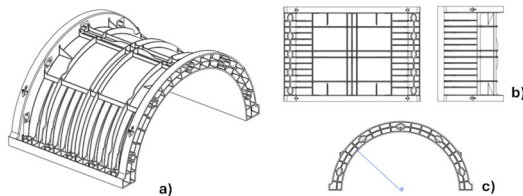


Figure 2. a) external axonometric view; b) lateral and external view; c) plan view.

The experimental design adopted a cylindrical body as the core element of the apparatus. This configuration was selected for two principal reasons. Firstly, in field applications, permeation grouting is inherently three-dimensional and commonly executed through injection systems equipped with four valves positioned orthogonally (at 90° intervals) along the perimeter, with vertical spacing of approximately 33 cm. The cylindrical geometry was therefore considered the most consistent with the spatial distribution and operating principles of full-scale injection systems, ensuring greater fidelity in reproducing field conditions. Secondly, the cylindrical shape significantly reduces the potential for fluid and/or pressure leakage. Alternative geometries, such as cubic configurations, would inevitably introduce multiple junctions (i.e., edges and vertices), which are structurally more challenging to seal and prone to inducing boundary-related artefacts. The cylindrical body thus represents the most reliable solution, both in terms of geometric consistency and in ensuring the hydraulic tightness required for controlled laboratory modelling. The cylindrical chamber employed in the experimental setup was constructed from Acrylonitrile Butadiene Styrene (ABS) and designed to function as a formwork (Figure 2). The chamber has a total height of 605 mm, an internal diameter of 700 mm—selected to replicate the typical centre-to-centre spacing of injection pipes in field applications (approximately 700)—and a wall thickness of 82 mm. The volume of soil subjected to treatment corresponds to the internal diameter of the chamber and a height of 350 mm. To achieve the required soil height of 350 mm, an extension of 250 mm was incorporated at the base of the chamber. This extension was produced by initially casting a mixture of polyurethane resin and expanded clay within the formwork, subsequently overlaid with a water-quick-setting

cement mixture to provide surface levelling and ensure a uniform support base.

The upper part of the CC is similar to the lower one. It also consists of a 1 m x 1 m wooden panel, 30 mm thick, treated to reduce the risk of swelling due to the absorption of water and/or injection mixtures. Two U-shaped steel bars are positioned above this lid, perpendicular to the formwork closure point. These are connected by threaded rods to the other two U-shaped steel bars placed under the base, to ensure structural tightness and reduce deformation. Also, the panel has a total of 14 holes, divided as follows: 10 holes (\varnothing 8 mm) allowing the passage of M8 screws (100 mm long) to attach the panel to the cylindrical formwork; and 4 holes (\varnothing 10 mm) for M14 threaded rods approximately 1 m long, used to connect the top and base panels (Figure 2b). In this case, too two rubber sheets with distinct functions are positioned between the upper edge of the formwork and the closing panel. The first sheet, 2 mm thick and cut into a ring shape, acts as a gasket to ensure the hydraulic tightness of the system. On top of it, a second sheet of rubber, 5 mm thick, is clamped between the formwork and the panel and used to simulate the lithostatic load. For this purpose, a hole is made in the panel and connected to a compressed-air line: by regulating the applied pressure, the rubber sheet inflates and exerts a force on the soil, reproducing the lithostatic stress corresponding to the target depth. A central hole with a diameter of 80 mm is made in the panel to allow the insertion of the tube-à-manchette (TAM). To counteract the forces generated by the injection pressures, an anti-extraction flange is installed in combination with a flat flange. For this purpose, four additional through-holes (\varnothing 10.2 mm) are drilled around the main opening to anchor the flanges. Finally, to prevent pressure dissipation and upward leakage of the grout along the TAM through the central hole, a rubber nozzle (\varnothing 80 mm) is bonded to the rubber sheet, extended inside the hole, and clamped by the anti-extraction flange, thereby providing additional sealing of the system.

2.1.1 Drainage system and pressure tanks

The drainage system is composed of 8 holes: 4 positioned at 90° from the joint between the two semi-formworks and 4 aligned along the joint, identified as a critical zone for potential grout and pressure leakage. The holes are arranged at two distinct elevations in a vertically mirrored configuration, ensuring geometric symmetry and balanced distribution.

Holes along the formwork connect the soil to the outside. A geonet–geotextile drain placed between the holes and the chamber wall promotes uniform flow towards the outlets. The holes discharge either into collection containers or into pressurized tanks, the latter allowing confinement of the pore fluid and simulation of in-situ hydrostatic pressure. The soil tanks are made up as follows. A polycarbonate cylinder with a 20 cm diameter represents the central body and two 50 x 50 cm wooden panel are used as the base and the top of the tank. These components are secured by a rigid framework consisting of four M8 threaded bars, which provide structural stiffness and ensure resistance against the internal pressures generated during operation, even though such pressures are relatively low. On the top, there are 3 holes. The first one (a) links directly the tank to the drainage system of the CC; the second one (b) is for the water load and the third (c) for the air pressure. The latter one is directly linked to the compressed air line and, via a system with a pressure gauge and pressure regulator, allows to control the hydrostatic pressure inside the soil sample.

2.2 On-site equipment

The system design introduces the innovation of enabling the direct use of field equipment under laboratory conditions. This allows to replicate field injection conditions as accurately as possible, while maintaining direct control over all factors and variables influencing the injection process. The injection installation used with the CC described above consists of: injector and turbomixer, injection stand, double packer and a *tube a manchettes* (TAM).

The preparation of the grout mixtures was carried out using the MDPT150-DEOL3 system, comprising a turbomixer and an injector. The system is equipped with a digital control interface that enables the specification of injection parameters for each valve of the tube-à-manchette and provides real-time monitoring of the injected volume, pressure, and flow rate during the grouting process.

The mixture flow across the broad during injection is monitored using an injection stand equipped with a manometer and a flowmeter. The first one is to control pressure trends. The second one is for flow monitoring.

Valve tubes (Durvinil, $\text{Ø}_i = 40 \text{ mm}$, $\text{Ø}_e = 48 \text{ mm}$) with external valves and sealing rings are used. The tube, every 33 cm, has 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. It has DUR-O-RING hand valves that provide several operational advantages. First, they enable selective injections, allowing the operator to choose the valve to be activated and to record both pressure and injected volumes over time, for instance through a data logger. Second, they permit repeated injections, as the valves ensure complete closure after each cycle, thereby maintaining functionality for subsequent use. Moreover, they allow flexibility in the type of grout mixture employed, including standard cement, microfine cement and silicate-based formulations.

Finally, a double hydraulic packer was employed to perform the injections through the valves. This device enables the isolation of each individual valve to be treated. The system operates with oil: pressure is applied to the hydraulic circuit by means of a manual pump, causing the rubber seals to compress and expand radially. In this way, the packer isolates the volume surrounding each valve, ensuring that the grout mixture is injected into the soil in a controlled manner, valve by valve, while allowing precise regulation of the volume discharged through each outlet.

3 TEST PROCEDURE

3.1 Pre-injection tests

Before the real injection, all the elements characterizing the injection are defined through several tests that make possible to evaluate the groutability of a specific soil. These are distinguished in soil characterization and mixture characterization.

3.1.1 Mixture characterization:

These two types of mixtures are commonly used in practice and have also been adopted in this work (Table 1; Burwell et al., 1958):

- **Cement mix:** a suspension constituted of water, Portland type cement CEM II/B-LL 42.5R, bentonite (Bentonite Y, with sodium ions) and dispersing additive (Lamperse BV). The proportions chosen These ratios were chosen to obtain a mixture with a viscosity and stability such that would allow it to permeate the voids in

the soil at low injection pressures (3 bar) and without press filtration pressurization phenomena.

- **Silicate mix:** a solution constituted of water, silica liquor, CaCO_3 as carboslurry and NaOH as a reagent (2022, Prochin). They are mixed in different proportions define as a function of the temperature of the working environment, distinguishing *summer*, *winter* and *intermediate* formulas.

Table 1. Mixtures used for injections.: Cement mix proportions relative to cement.; Silicate mix components (W: water; S: silica liquor; C: carboslurry; N: reagent) as the quantities [g] per liter of mixture.

CEMENT MIXTURES				
	W/C	B/C	Add/C	Soil
Cem_mix#1	2.65	0.1	0.01	b)

SILICATE MIXTURES					
	W	S	C	N	Soil
Sil_mix#1	0.39	0.37	0.24	0.28	b)

Mixtures are characterized in terms of viscosity, density and stability over time to determine the behaviour of mixtures during and immediately after the injection. Tests to characterize mixtures' properties:

- **Fluid viscosity:** determined using a Marsh funnel (viscosity measured in terms of efflux time) and a hand-crank rheometer (viscosity evaluated from the fluid response to rotation at 300 and 600 rpm).
- **Fluid density:** determined as the mass per unit volume using a graduated cylinder and verified with a Baroid mud balance.
- **Fluid stability:** assessed through bleeding and filter-press tests. These tests were performed only on cement mixtures, as they are suspensions.

3.1.2 Soil characterization

Injections can be performed on: (a) standard soils sourced from quarries; (b) soils reconstructed by mixing standard soils; and (c) real soils collected from the field. The injectability of a soil to different grouts depends primarily on its particle size distribution (PSD). Pettinaroli et al. (2019) identified injectability curves for the two main types of mixtures, as shown in Figure 3. If the particle size distribution of the soil to be injected lies to the left of the injectability curve, the soil can be considered injectable with that grout. In this work, soil type (b) was used for injection under dry conditions. It was reconstructed by mixing 5 standard soils to obtain a soil that was partially injectable with the cement-based grout and fully injectable with the silicate-based grout (Figure 3).

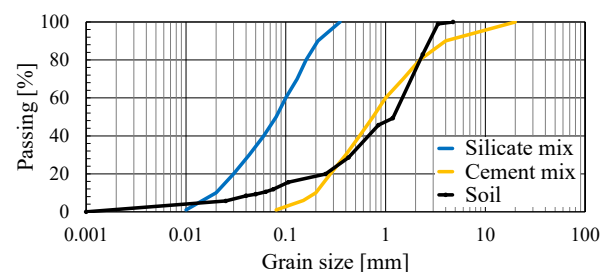


Figure 3. PSD for soil specimen and groutability curves for: cement mix (yellow) and silicate mix (blue).

The rheological characterization of the mixtures was followed by mechanical testing, in which uniaxial compressive strength and stiffness were measured as reference values to assess the effects of injection. Mixing procedures were kept

consistent for both types of grouts. The cement-based grout was prepared by blending water, additive, and bentonite into a slurry, allowing it to rest for 10 minutes, and then adding cement and mixing for a further 10 minutes. The silicate-based grout, being more temperature-sensitive, was mixed in shorter steps: water and sodium silicate for 5 s, calcium carbonate for 5 s, and sodium hydroxide for 300 s. Each mixture was prepared twice with different batch volumes and mixing equipment. Preliminary tests on 5 L batches were performed using a drill and whisk, whereas validation for the 3D system was carried out on 30 L batches using on-site mixers, following the same sequence and timing.

3.2 Injection in CC

The TAM (\varnothing 40/48 mm) is positioned at the centre of the cylindrical system, around which a casing pipe (\varnothing 100 mm) is installed, to allow the subsequent casting of the bentonite sheath. The granular soil is then placed in the chamber in layers and compacted to obtain 240 kg of soil within a known volume of 130 lt, corresponding to an average porosity of 30%. Once the soil preparation is completed, the volume between the TAM and the soil is filled with the bentonite sheath. The casing pipe is gradually withdrawn during this process, and the sheath is then allowed to cure for 2-3 days.

The soil (Figure 3) described in the pre-injection test section was injected using the so-called *Metodo Milano* with two distinct mixes (Table 1) with an imposed flow rate of 5 lt/min. The first was performed using a cement mixture while the second one using a silicate mixture. During the injection phase, the use of the real-scale injector allowed continuous monitoring and recording of all relevant parameters, namely injected volume, injection pressure, and flow rate.

3.3 Treated sample extraction and laboratory testing

Following injection, a curing period of 28 days was imposed to allow the grout mixtures to cure. At the end of this period, specimens were extracted from the treated soil.

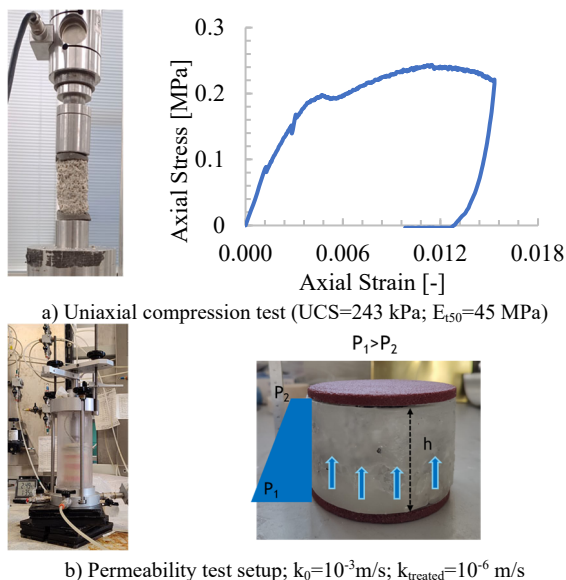


Figure 4. Example of the results obtained from mechanical and hydraulic tests.

Depending on the soil grain size and the degree of cementation achieved by the grout after permeation, three extraction techniques were identified: manual trimming, core drilling, and circular saw cutting. In this case, the first technique was used to extract samples at 15 cm, for each direction, from the injection point. Once extracted, samples were tested both

under uniaxial compression tests and permeability tests, showing improvement of their mechanical and hydraulic properties. Mechanical properties have been increased. From the UCS test, a stress-strain curve is obtained and so the stiffness E , expressed as the slope of the tangent to 50 % of the peak strength (E_{50}), can be derived (Figure 4). This value is then compared with the stiffness of loose soil (E_0) obtained through an edometric test in displacement control. Tests showed that the injection resulted in an increase in stiffness of 2 to 4 times the E_0 value. Permeability, determined through constant head tests, reduces by 3 orders of magnitude after treatment (Figure 4b).

4 CONCLUSIONS

A new 3D calibration chamber was designed and built to reproduce permeation grouting under controlled laboratory conditions. The system integrates real field equipment (TAM, double packer, turbomixer) and a bentonite sheath, ensuring realistic simulation of in-situ processes. Key findings are that the chamber allows continuous monitoring of pressure, flow and injected volume during grouting; the bentonite liner proved essential to prevent preferential flow paths and stabilize the borehole. And finally, sequential injections with cement and silicate mixtures successfully improved soil strength and permeability. This apparatus represents a reliable tool to better understand permeation grouting mechanisms and to optimize field procedures through controlled laboratory testing.

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