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Grout injection in the laboratory

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ABSTRACT: Many grout injection devices have been described in literature. The design of our own injection procedure was strongly inspired by these previous works. However, we made it original by the tests systematically added to check its performances concerning the homogeneity and the reproducibility of the grouted samples. After it had been validated, three parameters were examined: the cement to water ratio, the rate of discharge of the grout and the nature of the soil. Mechanical tests were also carried out to control the quality of the procedure and to assess the effect of the parameters on the properties of the grouted soils, in particular the elastic properties in the small strain range. We proved that the cement to water ratio and the nature of the soil were the main influential parameters.

1 GROUTING AND INJECTABILITY

The injection, under pressure, of a microfine cement grout is a suitable technique in order to improve the geotechnical characteristics of a soil with an initial permeability between 10^{-5} and 10^{-3} m/s. The injection and the setting of the cement involve both the reduction of the porosity and the increase of the stiffness and the strength of the initial soil. Unfortunately, in situ conditions do not usually lend to an extensive study of the behaviour of the grouted soils. So the technique has been reproduced in the laboratory.

In many cases, the main purpose of an injection test in the laboratory is to assess the injectability of a grout in a given soil. Some useful injectability rules have therefore been proposed. A relatively complete review was already done by Benhamou (1994). Rather than injectability, injection tests in the laboratory now aim at the understanding of the physIcal or chemical mechanisms that occur whereas the grout permeates the soil. Another objective is to prepare homogeneous samples of grouted soils.

2 FORMER INJECTION EQUIPMENTS

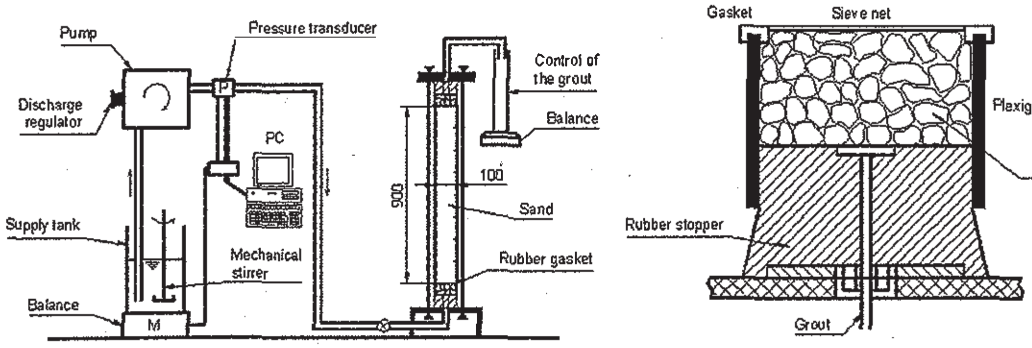
Many injection devices have been described in literature (Zebovitz et al. 1989, Di Prisco et al. 1992, Benhamou 1994, Schwarz et al. 1994, Bennabi et al. 1995, Azzar 1997, Tailliez 1998, Ismail et al. 2000) or in Standards (French Standard NF P 19-891, American Standard D 4320-93). All of them are mainly composed of a pump that allows to inject the grout and of a transparent cylindrical tube inside which the soil is deposited.

Those devices can be classified in three groups according to the height to diameter ratio (H/D) of the tube and the objectives of the grout injection (Table 1). A wide range of diameter, from 22 to 100 mm, was used by the practitioners. Nevertheless, it has been recognised that the smooth face of the tube and the wall effect could influence the filtration process by creating preferential paths for the grout into the soil (Azzar 1997). Consequently, the use of the greatest possible diameter D was advised.

The main part of our experimental set-up, as previous ones, is therefore a cylindrical and transparent tube made of a rigid Plexiglas with an internal diameter of 100 mm and an height of 900 mm (Fig. 1). We noticed that the grouted sand was not homogeneous over the complete volume of the tube when the soil was in direct contact with the rubber stoppers. We have assumed that the sudden reduction of the outlet diameter acted as a funnel where the finest particles concentrated, causing the soil in the upper section to be more reinforced. Another evidence was that relatively high injection pressures were recorded at the end of the injection step. Consequently two 50 mm thick filters composed of gravel with a diameter between 4 to 8 mm are hence interposed between the soil and the stoppers. Sieve nets are also set in place to separate the soil and the gravel in order to create a laminar flow of grout through the tested soil.

Table 1. Classification of the previous injection devices.

Height to diameter ratio H/D	Objective of the injection	References
H/D ≈ 2	Preparation of one homogeneous grouted sample	Standards, Bennabi et al 1995 Ismail et al 2000
6 < H/D < 10	Study of the filtration process and of the mechanical behaviour of several grouted samples	Benhamou 1994 Schwarz et al 1994, Tailliez 1998
H/D > 10	Filtration understanding	Bouchelaghem 2000



The injection device

Detail

Figure 1. Injection device.

3 EXPERIMENTAL PROCEDURE

The injection procedure consists of six successive steps: the setting of the equipment, the filling of the tube with the granular material, the preparation of the microfine cement grout, the grout injection itself, the storage of the tubes and finally the mechanical tests.

3.1 *Filling of the tube*

Two methods could be used to fill the tube with sand: by sand raining or by successive layers. The pluviation method (Levacher et al. 1994, Ismail et al. 2000) did not seem to be suitable for columns with high height to diameter ratios. So we have adopted the second method that consists in dropping the sand through a 1 m long hose surmounted by a funnel, placed inside the Plexiglas tube and slowly pulled up. Each 10 cm thick sand layer is then compacted by hammer strokes on the perimeter of the tube. The number and the intensity of these hammer strokes influence the homogeneity of the sand and the relative density index I_d, such as:

$$I_d = \frac{\gamma_{max}}{\gamma}\frac{\gamma - \gamma_{min}}{\gamma_{max} - \gamma_{min}} \qquad (1)$$

where γ, γ_{min} and γ_{max} are respectively the unit weight, the minimal unit weight and the maximal unit weight.

When no hammer strokes are applied, the relative density index is close to 40 % but a density gradient then appears inside the tube. When 30 strong hammer strokes are applied, the relative density index is close to 95 %. In this case, the reproducibility is good. We also established a procedure in order to obtain intermediate values of the relative density index but it has not been validated yet.

Once completely filled, the column is closed and tightened by means of compressed rubber gaskets. The sand is then saturated with water by an upward flow of 6 cm^3/s (or 21.6 l/h). This step can be removed if necessary.

3.2 *Preparation of the microfine cement grout*

The patented microfine cement grout used in this research program is composed of water, cement with particles size less than 12 µm, an inert additive and a superplasticizer which role is to disperse the cement particles. Precise contents of each component are prepared and mixed together according to a prescribed order. The suspension is simultaneously energetically stirred in an agitator supply tank in which the grout batch is 4000 cm^3. The Rayneri high-speed paddle mixer has not been changed for the duration of the study since Schwarz et al. (1994) have enhanced the influence of the mixer on the rheological behaviour of the grout.

Since the grout is ready, we determine its density ρ_{grout} and its rheological properties. The density is measured with a Baroïd scale. As a microfine cement grout has often been considered as a binghamian fluid, we also characterise it by its plastic viscosity η_p and its yield shear stress τ_p. The viscosity is measured by means of a Fann viscometer or evaluated from a Marsh flow cone in which a predetermined volume of grout is permitted to escape through a precisely sized orifice, the time of efflux being used as the indication of the grout consistency (ASCE 1980). These properties mainly depend on the cement to water ratio C/W. Table 2 shows the properties of the grout for 3 mix designs corresponding to cement to water ratios of 0.172, 0.299 and 0.437. Finally we check that these properties are constant over the working time, namely about 20 minutes, provided that the stirring action with a special propeller is maintained to avoid flocculation and segregation of the cement particles.

Table 2. Rheological properties of the grouts.

C/W	ρ_{grout} *g/cm^3*	η_p *cPo*	τ_p *Pa*	η_{Marsh} *s*
Pure water	1.00			27
0.172	1.17	2.5	1	29
0.299	1.23	3	1	29.5
0.437	1.27	3.5	1	29.8

3.3 *Grout injection*

A fixed volume of grout is injected from the base to the top of the column with a constant rate of discharge. We record the evolution of the mass, of the position of the injection front and of the injection pressure. We also control the rheological properties of the grout when it left the column.

After injection, the tubes are stored in water, 28 days at least, until the cement setting provides a sufficient strength to the grouted sands. Three samples are finally cut out in each column. Their faces are perfectly aligned. Their height to diameter ratio is close to 2.

4 INJECTION ANALYSIS

4.1 *Granular soils tested*

Following the procedure described above, three different granular soils were tested: a standard siliceous fine Fontainebleau Sand (noted SF) and two silico-calcareous alluvial deposits (noted AAM and AAG). Their characteristics are reported in Table 3 (D_x is the grain size corresponding to a passing of x %). The shape of the particles was quite similar for the three soils. Their grading curve (Fig. 2) was cut to a particle size of 1 cm.

Table 3. Properties of soils tested.

Soil *Unit*	D_{50} *μm*	D_{60}/D_{10}	γ_{min} *kN/m^3*	γ_{max} *kN/m^3*
SF	220	1.4	14.0	16.5
AAM	410	2.1	14.9	17.9
AAG	1300	5.9	16.4	19.4

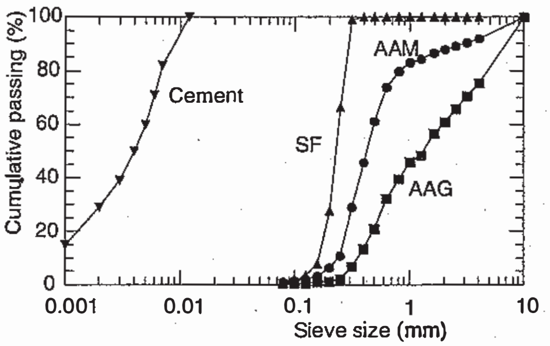


Figure 2. Grading curves of the sands and the cement grout.

4.2 *Follow-up of the injection parameters*

The monitoring of the injection parameters, namely the pumping rate q, the injection pressure P, the mass M and the position of the grout h in the tube, as a function of the time t, allowed to qualitatively appraise the quality of the grout permeation.

As the pumping rate q was set to a constant value, the mass of the grout injected into the soil had to linearly evolve with time, which was confirmed for all the tests. More, the velocity of the injection front, easily obtained by noting the height of the grout in the tube and the corresponding time, was a good indicator of the homogeneity of the soil density. Irregular velocities revealed an heterogeneity in the sand due to segregation of the soil particles or a larger size of the grains for instance.

In the same way, the grout permeation had to occur with a regular pressure increase until the grout reached the top of the column. A pressure fall means either a leak or a breakdown in the soil. We observed such an horizontal breakdown in a soil with a low relative density index. It very likely corresponded to an auto-compaction phenomenon. In general, due to the low pumping rate and the rheological properties of the grout, injection occurred without any problem.

Figure 3, with the corresponding characteristics of the tests in Table 4, shows the effect of the cement to water ratio and the nature of the soil in the development of the injection pressure. The relative density index was 95 % for the three soils. We noted that the higher the cement to water ratio was, the greater the injection pressures were. Smaller mean diameters of soil particles also seemed to induce stronger injection pressures.

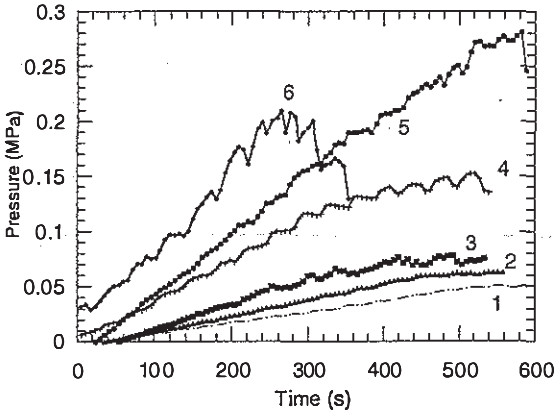


Figure 3. Follow-up of the grout pressure.

Table 4. Characteristics of injection tests.

Test	Soil	C/W	q cm^3/s
1	SF	Pure water	6
2	AAM	0.172	6
3	AAG	0.172	6
4	SF	0.172	6
5	SF	0.235	6
6	SF	0.172	8.77

4.3 *Homogeneity of the grouted sands*

Schwarz et al. (1994) have noted a decrease of the unconfined compressive strength with the growing distance from the point of injection. This was all the more obvious as the cement to water ratio was high. Consequently, we have assessed the degree of heterogeneity of the grouted sand density in a tube by means of a gammadensimeter.

Figure 4 shows such a measure on a grouted Fontainebleau sand sample (I_d=95 %, C/W=0.172). The mean unit weight of the grouted sand was 20.4 kN/m^3. The succession of humps and hollows was clearly due to the method for filling the tube with sand. However, the variation around the mean value was relatively low, about ± 2 %.

5 MECHANICAL TESTS

The elastic properties of grouted soils in the small strain domain ($\varepsilon < 10^{-5}$) are of great importance for structural design. Their determination requires the use of special testing methods among which wave propagation testing devices. Unconfined compressive tests are also of practical interest for a first estimate of the mechanical improvement of the grouted sands. In our case, these tests also allowed to check, after injection, the homogeneity of the grouted samples.

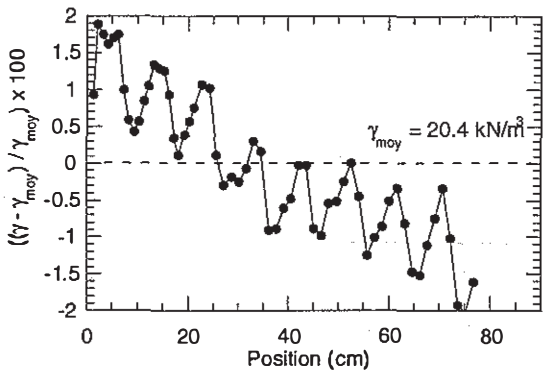


Figure 4. Result of a gammadensimeter test.

5.1 *Experimental equipment*

Two laboratory testing devices were used to determine the dynamic elastic properties of both the grouted sand and the pure grout in the small strain range: the GrindoSonic apparatus (Allison 1987, Allison 1988, French Standard NF P 18-414) and an Ultrasonic Concrete Tester (French Standard NF P 18-418). Both are non-destructive methods.

The GrindoSonic apparatus consists in exciting the sample by a slight mechanical impulse. The fundamental vibration frequency is deduced from the analysis of the resulting transient vibration pattern and the elastic parameters are then calculated. Accurate performances are obtained for Young's moduli varying from 100 MPa to 840 GPa. They mainly depend on the shape of the samples and of the physical characteristics of the materials. Two pulse mode among the three following mode (bending, torsion, compression) are required to determine the Young's modulus E_g, the Poisson's ratio ν_g and the shear modulus G_g.

Allison (1988) also indicated that the dynamic elastic parameters depend on the water content of the tested material. For this reason, our samples were stored in the same conditions of relative humidity and temperature. They were dried in the open air before any measurement.

The Ultrasonic Concrete Tester E46 consists in measuring the time T corresponding to the propagation of an ultrasonic longitudinal wave through the tested material. Two transducers are placed on each end of the samples. A good contact is assured by means of a scan gel. An accurate determination of the length L of the sample is also required to calculate the velocity V_{us} of the ultrasonic wave. Strains are small enough to assume a linear elastic behaviour of the material. From this, it can be shown that:

$$E = \rho V_{us}^2 \frac{(1+\nu)(1-2\nu)}{1-\nu} = \rho\left(\frac{L}{T}\right)^2 \frac{(1+\nu)(1-2\nu)}{1-\nu} \qquad (2)$$

where ρ is the density of the grouted sand. As the Poisson's ratio can not be determined, we only compare the longitudinal wave velocity.

5.2 *Experimental results*

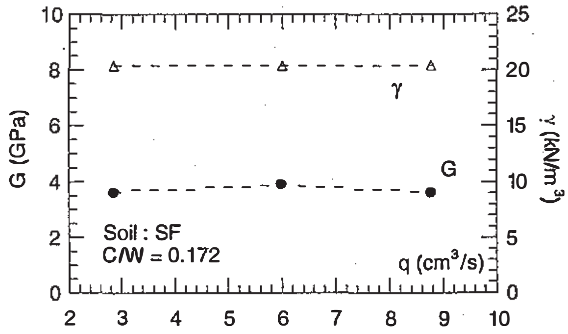
We show in Table 5 the experimental results as a function of the cement to water ratio C/W, the rate of discharge of the grout q and the nature of the soil. G_g is the shear modulus determined by the GrindoSonic apparatus, E_g the Young's modulus, V_{us} the velocity of the ultrasonic wave measured with the Ultrasonic Tester, γ the dry unit weight. The subscript m stands for the mean value and Δ for the difference between the minimal and the maximal values of a given property.

5.3 *Comments*

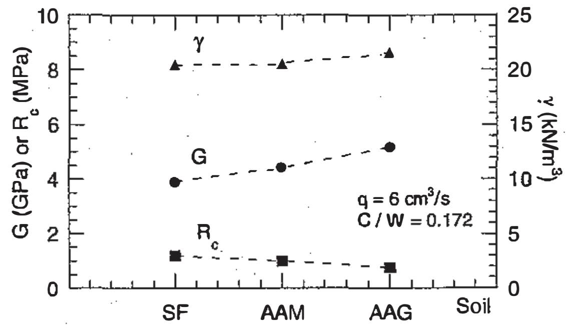
Grouted sands prepared in the same conditions led to very similar elastic properties as shown in Table 5. In the same way, the mechanical tests confirmed the previous observations about the homogeneity of the grouted sand in a tube. Indeed, the dynamic elastic properties of three samples stemmed from the same column seemed to be quite similar, except for the test No. 5 for which the preparation probably caused damage in the samples. The small variations can be attributed to a small variation in the local density or in a more important content of coarser grains that favour the propagation of mechanical waves.

If we consider that the value of the Poisson's ratio determined by the GrindoSonic apparatus is acceptable and if we report this value in Eq. 3, the dynamic elastic moduli measured by the GrindoSonic apparatus and by the Ultrasonic Tester present differences between 12 to 52 % in favour of the latter. This can be attributed to the stratification observed in Figure 4. Indeed, the GrindoSonic apparatus provides a fundamental frequency typical of the whole sample. On the contrary, the Ultrasonic Tester provides a propagation time dependent of the internal structure of the samples, in particular of the anisotropy induced by the preparation method. That is the reason why we hence recommend to take precautions as for the interpretation of the ultrasonic unidirectional test results.

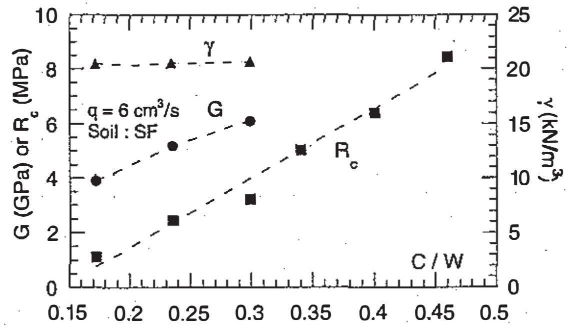
Some experimental results are shown in Figure 5. We briefly indicate that the rate of discharge of the grout has little influence on the shear modulus. The nature of the soil also appears to have an effect on the shear modulus, but inversely of the unconfined compressive strength, through the stiffness of the grains themselves, their size, their roughness. Finally, for a given soil, the shear modulus and the unconfined compressive strength linearly depend on the cement to water ratio.



(a) Effect of the rate of discharge q.



(b) Effect of the nature of the soil.



(c) Effect of cement to water ratio C/W.

Figure 5. Evolution of the elastic parameters.

6 CONCLUSIONS

The experimental results described in this paper represent a first step in a more ambitious research program related to the behaviour of grouted sands. Our first preoccupation was therefore to establish a reliable method to reproduce improved soils. The injection procedure was consistent with our expectations in terms of homogeneity and reproducibility that have been controlled by different ways, during the injection as well as after the setting of the cement. We performed some mechanical tests that proved these statements. Further step will be to compare elastic properties of grouted sands prepared in the laboratory and the ones of grouted sands injected in situ by means of sleeved grout pipes.

Table 5. Experimental elastic parameters.

Test Units	Soil	q cm^3/s	C/W	$G_{g,m}$ GPa	$\Delta G/G_{g,m}$ %	$E_{g,m}$ GPa	$\nu_{g,m}$	$V_{us,m}$ m/s	$\Delta V/V_{us,m}$ %	γ_m kN/m^3	$\Delta\gamma/\gamma_m$ %
1	SF	6	0.172	3.9	1.0	9.1	0.18	2640	3.3	20.44	1.3
2	SF	6	0.172	3.9	2.6	9.1	0.19	2603	4.8	20.54	0.8
3	SF	6	0.235	5.2	1.6	12.4	0.18	2895	2.9	20.55	1.0
4	SF	6	0.299	6.1	5.4	15.7	0.22	3087	2.1	20.68	1.2
5	SF	2.84	0.172	3.7	23.4	8.4	0.15	2397	20.1	20.41	0.2
6	SF	8.77	0.172	3.6	3.6	8.6	0.19	2503	2.6	20.51	0.8
7	SF	8.77	0.172	3.6	4.4	8.4	0.15	2545	3.2	20.37	0.7
8	SF	8.77	0.172	3.7	2.4	8.5	0.16	2568	2.0	20.46	0.8
9	AAM	6	0.172	4.4	9.8	11.1	0.20	2778	6.0	20.62	0.5
10	AAG	6	0.172	5.2	2.7	11.9	0.14	2790	10.9	21.60	0.8
11	Pure Grout	-	0.172	0.47	-	1.35	0.44	1870	-	11.48	-

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