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Research paper

Influence of technological parameters on the properties of jet grouting columns detected with full scale experiments

Lidia Wanik[1], Joanna Bzówka[2], Giuseppe Modoni[3]

Abstract: Jet grouting induces a complex interaction between soil and injected fluids, and thus the properties of columns are dictated by a combination of the two systems. Aiming to improve the efficiency of projects and optimize execution, past research has focused on the prediction of the column properties understanding the mechanisms underlaying treatment execution. For the complexity of phenomena and the uncertain determination of soil properties, the question can be only partially addressed on the theoretical level, being important answers left to the empiricism of field trials, i.e. full scale experiments carried out to test specific jet grouting solutions on specific sites. The present paper reports the results of a field experiment whose peculiarity consists in being conceived to investigate the role of technology on a wider spectrum. Single and double fluid injection systems with various parameters have been simultaneously performed on a subsoil characterized by in situ tests. Columns have then been discovered to measure their diameter and samples of cemented material have been cored and subjected to uniaxial compressive tests. Results are herein summarized and compared with literature solutions to point out strength and deficiencies of currently adopted conceptual models.

Keywords: jet grouting, single fluid system, double fluid system, field trial tests, geometry prediction of jet grouting columns

[1]PhD., Eng., Academy of Silesia, Faculty of Architecture, Civil Engineering and Applied Arts, Rolna 43, 40-555 Katowice, Poland, e-mail: lidia.wanik@wst.com.pl, ORCID: 0000-0001-9474-7639
[2]Prof., DSc., PhD., Eng., The Silesian University of Technology, Faculty of Civil Engineering, Akademicka 5, 44-100 Gliwice, Poland, e-mail: Joanna.Bzowka@polsl.pl, ORCID: 0000-0002-1765-7354
[3]DSc., PhD., Eng., University of Cassino and Southern Lazio, Faculty of Engineering, via di Biasio 43, 03043 Cassino, Italy, e-mail: modoni@unicas.it, ORCID: 0000-0001-9200-2502

1. Introduction

Jet grouting is one of the most used ground improvement techniques, mostly thanks to its well acknowledged efficiency coupled with the flexibility of equipment that enables application in a wide range of contexts and soil types [1–5]. Briefly, the technique consists in drilling small holes into the ground and performing high-speed jets of fluids to erode soil, mix it with a binder and form cemented columns of circular, more rarely elliptical, section. The variety of available jet grouting systems is traditionally grouped in three different classes, according to numbers of fluids injected into the ground:

– single fluid – where grout is only injected to simultaneously erode and cement soil;
– double fluid – where the jet of grout is shrouded by a coaxial jet of compressed air to enhance the cutting efficiency;
– triple fluid – where erosion is produced by a jet of water shrouded by compressed air and cementation of the remolded soil is given by retarded jet grout injected from a lower nozzle [6].

Jet grouting columns can also be arranged in different geometrical layouts to form structural elements of various shapes [7–9]. Newer versions based on the use of small equipment are also possible, enabling to work in relatively narrow spaces and extend applicability to the rehabilitation of existing buildings [1–3, 10–15].

As is typical of all ground improvement solutions [16–18], results are dictated by a combination of technological factors and subsoil conditions. In this case, effects are dictated by the capacity of the jet to disintegrate the original soil fabric, mix homogeneously particles and grout, accomplish the cement reaction. An effective application of the techniques would thus require setting the technological factors in order to achieve the desired properties of columns, but this implies a capability to estimate dimension and mechanical properties of columns prior treatment are executed. However, the uncertainty connected with soil characterization and the not fully understood role of technology has the effect of increasing cost and time in construction projects, being it coped with conservativeness. A meaningful effort has been spent by researchers to establish relations among soil properties, technological factors and treatment results, in some cases adopting a phenomenological approach, i.e. inferring empirical relations among observed data, in other cases exploring the basic mechanisms of column formation and building conceptual and analytical predictive models. Empirical estimates proposed in the literature based on the interpretation of individual case studies (e.g. [10]), have the value of inferring a dependency of column properties with paramount factors but lack of generality and sometimes mismatch with other field evidence [5, 19]. The alternative is to build a robust conceptual model, based on a deeper knowledge of the involved mechanism, to schematize the influence of the treatment parameters on the outcomes of the jet grouting process. However, uncertainties stem from the complexity of mechanisms triggered by the technique, that involves highly turbulent multi-phase jets [20] eroding soil and mixing with particles. Moreover, the understanding of phenomena is complicated by the inability to visualize them with laboratory experiments, basically due to the very large energy involved in jet grouting and the paramount role of turbulence. So far, a possibility consists in interpreting phenomena indirectly from site observation, i.e.

deriving predictive solutions on a theoretical level [21] and seeking confirmation from the comparisons with produced effects (columns diameter, mechanical strength).

Goal of this paper is to explore relations with the results of true scale experiments. A field trial has been carried out at Bojszowy Nowe in Poland [19] specifically with this purpose. Sixteen columns, eight with single and eight with double fluid jet grouting, have been created up to a depth of 4 m, varying the set of parameters (injection pressure, nozzle diameter and rotational speed of the monitor) to observe the effects of injection on the geometrical characteristics of the columns and on the mechanical properties of the jet grouted material.

2. The Bojszowy Nowe field trial

2.1. Site characteristics

The trial field has been set in the municipality of Bojszowy Nowe (Upper Silesia-Poland). Before performing jet grouting, the subsoil has been investigated with two continuous boreholes and four Cone Penetration Tests with pore water pressure measurement (CPTU) [22] run up to the depth of 10.0 m (Fig. 1a). Based on the analysis of these repetitive results (Fig. 1c), the geotechnical profile of the site is schematized with four different layers (Fig. 1b).

– I layer – from 0 to –0.30 m below ground level, soil embankment built of topsoil and sand,
– IIa layer – from –0.30 to –2.30 m below ground level, medium sands with mean values of geotechnical parameters: $I_D = 44\%$, $\phi' = 31.9°$, $M_0 = 25.1$ MPa,
– IIc layer – from –2.20 to –3.5 m below ground level, plastic clays and muds with mean values of geotechnical parameters: $I_C = 0.62$, $\phi' = 19.0°$, $c' = 9.2$ kPa, $M_0 = 7.8$ MPa,
– IIb layer – from –3.50 to –10.0 m below ground level, medium sand with mean geotechnical parameters: $I_D = 78\%$, $\phi' = 36.5°$, $M_0 = 98.4$ MPa.

The groundwater table was noticed at the depth of 4.5 and 4.9 m below ground level (see Fig. 1b).

2.2. Layout of jet grouting columns

The columns layout consists of eight columns formed by a single fluid jet grouting system ($1S \div 8S$ in Fig. 1a) and eight columns formed by a double fluid jet grouting system ($1D \div 8D$ in Fig. 1a). All columns are injected from 0.5 m to 4.5 m below ground level and thus have 4.0 m length. Single and double fluid columns were conceived with a primary-secondary sequence on linear arrays with a 2.0 m spacing, considering this distance sufficient to avoid overlapping. However, when double fluid treatment was performed, some boiling was observed in previously injected fresh columns revealing a connection of the cemented bodies through the organic soil layer (IIc in Fig. 1b). This occurrence suggested to modify the pre-determined columns array, giving the irregular spacing of double fluid columns shown in Fig. 1a, and reconsider the time interval between treatments.

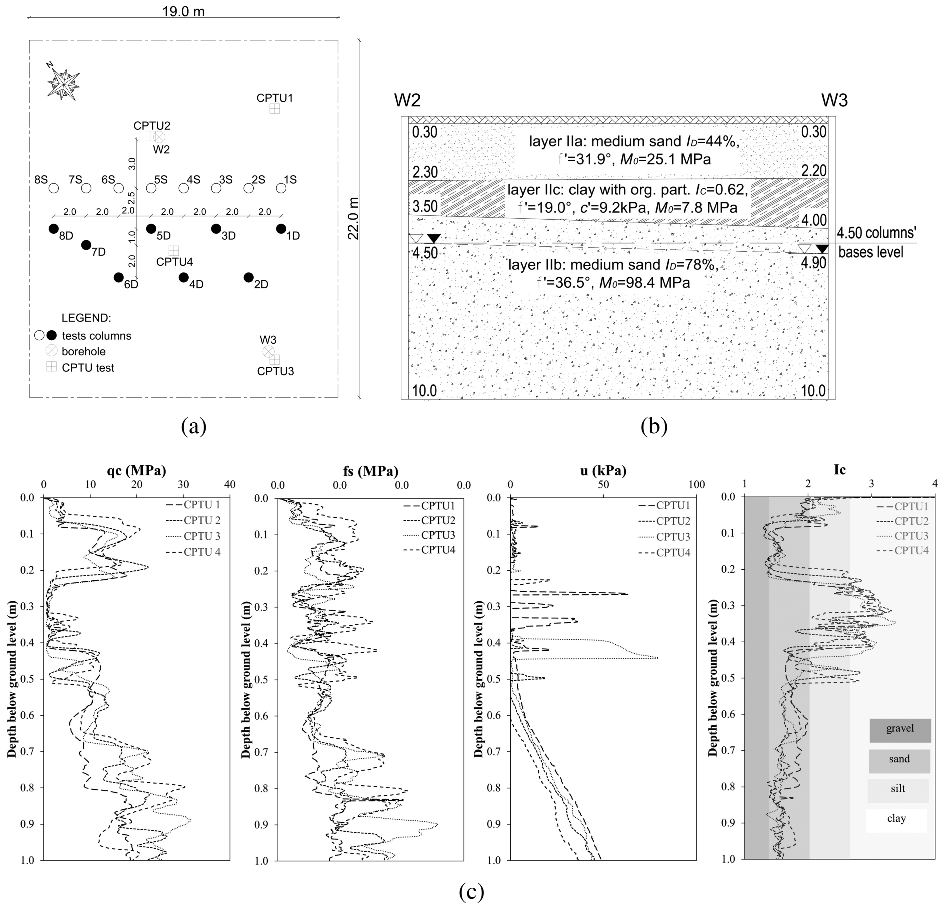


Fig. 1. (a) plan view of the Bojszowy Nowe test site with the layout with jet grouting columns, boreholes and CPTU tests, (b) geotechnical scheme of the subsoil, (c) CPTU profiles and interpretation with Robertson [23]

The jet grouting plant consisted of high-pressure pump, mixers, silo, air compressor (used for installation of double fluid columns) and drilling rig (MDT Mc 180B). During installation, the paramount technological parameters of jet grouting (time, drilling tool depth, drilling fluid pressure, flow rate, rotational speed, torque) were assigned and monitored by a computerized system. In particular, the following parameters were fixed:

- water/cement ratio by weight $\Omega = 1.0$ giving a grout density $\rho_g = 1.5$ g/cm^3,
- cement type: CEM II/B-V 32.5 R,
- number of nozzles: $M = 2$ pcs,
- average lifting speed: $V_{S1} = 8.3 \cdot 10^{-3}$ m/s (obtained with discontinuous lifting steps of $\Delta z = 40$ mm achieved each $t = 4.8$ s interval); in some columns a double pass of the monitor was achieved with the same procedure, so an average lifting speed of the monitor equal $V_{S2} = 4.15 \cdot 10^{-3}$ m/s is assumed in the next analyses,

– between each lifting step, one or two 360° degrees revolutions were applied to the monitor,
– air flow volume (for double fluid system): 5 m^3/min.

The remaining parameters were varied to assess their influence on the properties of columns:

– nozzle diameter for 2 pcs: $d_{01} = 2.8$ and $d_{02} = 4.0$ mm,
– grout pressure: $p_1 = 180$ (250) bar and $p_2 = 360$ bar,
– rotational speed of monitor: $\omega_1 = 12$ rpm and $\omega_2 = 25$ rpm.

The combination of technological parameters adopted for each column is summarized in Table 1.

Table 1. Values of jet grouting parameters assigned for each column in the Bojszowy Nowy test site

System	No. of column	Grout pressure p_g [bar]	Air flow volume [m^3 /min.]	Air pressure p_a [MPa]	No. of nozzle M [–]	Nozzle diameter d_0 [mm]	Rotational speed of monitor ω [rpm]	Average lifting speed V_S [mm/s]	Grout density ρ_g [kg/m^3]
Single fluid system	1S	360	–	–	2	4.0	25	8.30	1500
	2S	360	–	–	2	2.8	25	8.30	1500
	3S	180	–	–	2	4.0	25	8.30	1500
	4S	250	–	–	2	2.8	25	8.30	1500
	5S	360	–	–	2	4.0	12	8.30	1500
	6S	360	–	–	2	2.8	12	8.30	1500
	7S	180	–	–	2	4.0	12	8.30	1500
	8S	250	–	–	2	2.8	12	8.30	1500
Double fluid system	1D	360	5	0.7	2	4.0	25	8.30	1500
	2D	180	5	0.7	2	4.0	25	4.15	1500
	3D	360	5	0.7	2	4.0	12	8.30	1500
	4D	180	5	0.7	2	4.0	12	4.15	1500
	5D	360	5	0.7	2	2.8	25	8.30	1500
	6D	260	5	0.7	2	2.8	25	8.30	1500
	7D	360	5	0.7	2	2.8	12	4.15	1500
	8D	250	5	0.7	2	2.8	12	4.15	1500

2.3. Diameter of columns

About half a year after their execution, all sixteen columns were excavated up to a depth of 1.7 m below ground level (Fig. 2) with a small excavator and hand tools to prevent damage. Excavation had to be limited at this depth due to the instability of cuts, possibly induced by the presence of wet organic soil in the lower level. Above this height, heads and shafts of columns were cleaned to inspect them directly, measure dimensions

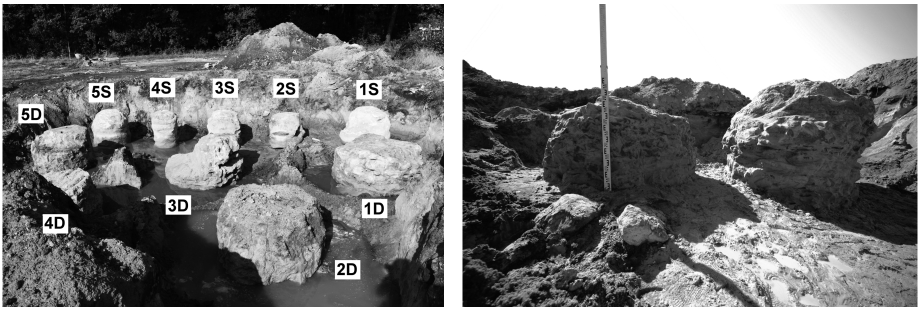


Fig. 2. Pictures of excavated columns [19]

and core samples from the center. Cross dimensions were obtained measuring the columns circumference every 10 cm depth along the shafts. As shown in Fig. 3, where the diameter of single and double fluid columns are reported versus depth, the dimensions of each column were rather constant, the difference among columns being ruled by the technological factors. Mean diameters range between 0.78÷1.13 m for single fluid columns (marked with "S" letter), between 1.54÷1.88 m for double fluid columns (marked with "D" letter) (Fig. 3).

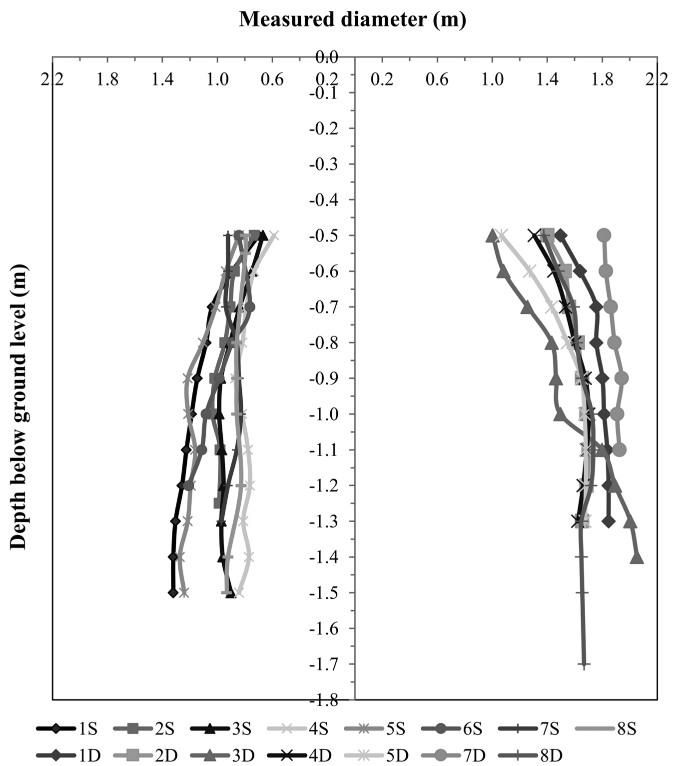


Fig. 3. Columns diameters profiles of single (left) and double fluid (right) columns versus depth

As also shown by the figures, the diameter of jet grouting columns at larger depth is bigger than near the surface. Indeed this occurrence is a voluntary effect, as the injection pressure was reduced when monitor approached the ground surface for the safety of workers. This effect has been neglected in the following analysis dedicated to prediction, computing the mean diameters of columns in the range of depths between 0.9 and 1.5 m where they are approximately constant.

2.4. Prediction

The influence of technology on the mean diameter of columns D_a has been explored grouping all parameters into a summarizing variable, i.e. the specific kinetic energy at the nozzle E'_n calculated with the following Eq. (2.1) [11]:

$$E'_n = \frac{\Pi}{8} \cdot \frac{M\rho d_0^2 V_0^3}{V_s} \tag{2.1}$$

where: M – number of nozzles, ρ – density of injected fluid, d_0 – nozzle diameter, V_0 – velocity of injected fluid at the nozzle, V_s – average monitor withdrawal speed.

The dependency of diameter on this cumulative variable is quite evident in Fig. 4, together with the effect of air wrapping of the jet achieved with the double fluid technique. The dot alignment is rather strict for single fluid columns, more scattered for double fluid columns possibly due to a less accurate control of the technique during execution. Notably, the rotational speed of the monitor ω shows a negligible influences on the values of diameter.

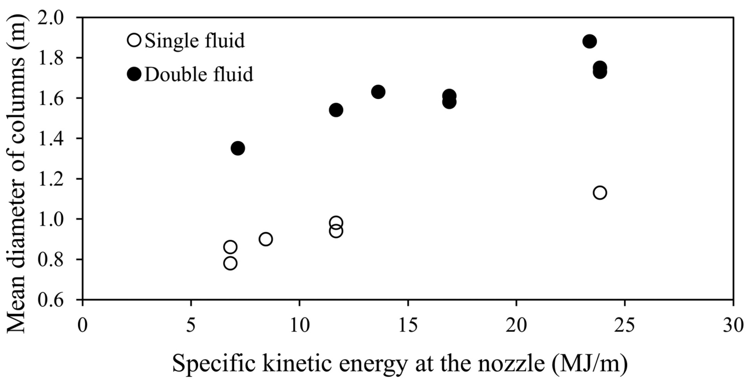


Fig. 4. Mean diameter of columns versus specific kinetic at the nozzle

The prediction was achieved with the formula proposed by Flora et al. (2013) [6]. The average diameter D_a can be calculated from the following relations:

– for fine-grained soils (E'_n in MJ/m and q_c in MPa):

$$D_a = D_{\text{ref}} \cdot \left(\frac{\alpha \cdot \Lambda^* \cdot E'_n}{7.5 \cdot 10}\right)^{\beta} \cdot \left(\frac{q_c}{1.5}\right)^{\delta} \tag{2.2}$$

– for coarse-grained soils (E'_n in MJ/m):

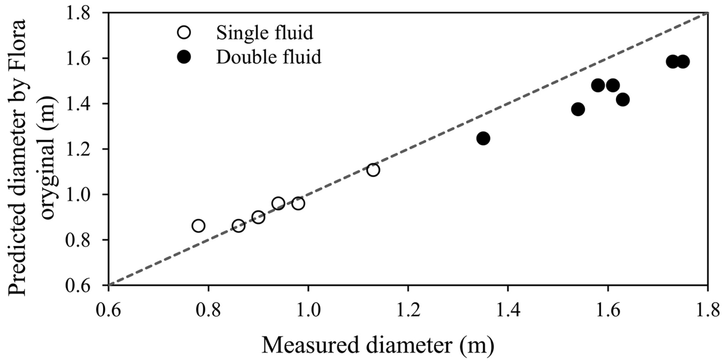
$$D_a = D_{\text{ref}} \cdot \left(\frac{\alpha \cdot \Lambda^* \cdot E'_n}{7.5 \cdot 10} \right)^{\beta} \cdot \left(\frac{N_{\text{SPT}}}{10} \right)^{\delta} \tag{2.3}$$

where: D_{ref} – diameter obtained with single fluid system having $\omega = 1$, $E'_n = 10$ MJ/m, $q_c = 1.5$ MPa or $N_{\text{SPT}} = 10$ depending on the soil type, α – parameter which quantifies the effects of the shrouding air jet in double and triple fluid systems ($\alpha = 1$ for single fluid system, $\alpha > 1$ for double and triple fluid system) (Table 2), Λ^* – parameter which depends on cement/water ratio by weight of the cutting fluid (Ω), $\Lambda^* = 7.5$ for $\Omega = 1$; for triple fluid system, in which water (without cement) is used as a cutting fluid ($\Omega = 0$), the value of Λ^* is equal 16 [1], E'_n – the kinetic energy at the nozzle per unit weight of column (Eq. 2.3), β, δ – parameters that are found by calibration with data obtained from literature and from the personal experience of the authors, $\beta = 0.2$ and $\delta = -0.25$ (Table 2), q_c – cone resistance measured by Cone Penetration Tests, NSPT – number of blows measured by Standard Penetration Tests.

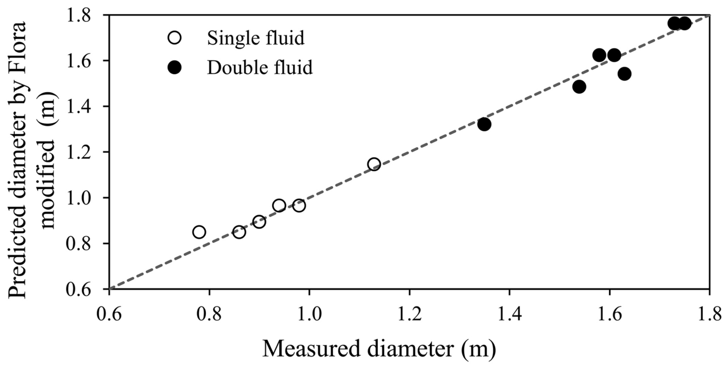
Table 2. Values of parameters to be adopted in the Eq. (2.2) and (2.3) for the prediction of diameters of jet grouting columns [6]

<table>
<tr><th colspan="2">Soil type</th><th>ASTM D2487 classification</th><th>D_{ref} (m)</th><th>β</th><th>δ</th><th>α (single fluid)</th><th>α (double and triple fluid)</th></tr>
<tr><td rowspan="2">Coarse grained</td><td>Without fine</td><td>Gravels and sands with < 5% fines (GW-GP-SW-SP)</td><td>1.00</td><td rowspan="3">0.20</td><td rowspan="3">–0.25</td><td rowspan="3">1</td><td rowspan="3">6</td></tr>
<tr><td>With fine</td><td>Gravels and sands with > 5% fines (GW-GC-SM-SC)</td><td>0.80</td></tr>
<tr><td>Fine grained</td><td></td><td>Silts, clay and organic soils (CL-ML-OL-CH-MH-OH-Pt)</td><td>0.50</td></tr>
</table>

Figure 5a shows the comparison of measurement with prediction made with Eq. (2.2) and Eq. (2.3), assigning the parameters of Table 2, as suggested by authors. Alignment on the 1:1 line is excellent for single fluid, less satisfactory for double fluid columns. This result is confirmed by the value of mean absolute error (MAE), equal to 2.4% (and standard error of the mean SEM equel to 0.012) in the case of single fluid, 10% in the case of double fluid (SEM equel to 0.011). Additionally, a systematic underestimation of diameter is provided by the prediction of double fluid jet grouting columns. This occurrence is in agreement with observation provide by different authors (e.g. [24]) who noticed an underestimate of diameter given by the formula of Flora et al. (2013) [6] for higher energy treatments. A modification of the exponent β from 0.2 to 0.24 in Eq. (2.2) and Eq. (2.3) leads to improve only slightly the prediction for single fluid, with MAE becoming equal to 2.3% (SEM equal to 0.01), but to substantially reduce error for double fluid jet grouting, with MAE equal to 3.0% (SEM equel to 0.008) (Fig. 5b).



(a)



(b)

Fig. 5. Comparison between measured and predicted diameter for single (SF), double fluid (DF) jet grouting columns. Prediction has been performed with Eq. (2.2) and Eq. (2.3) assigning the parameters of Table 2 (a) and modifying the exponent β to 0.24 (b)

This observation confirms the larger effectiveness of jet grouting achieved at higher energies. A possible explanation can be found from the numerical study carried out by Modoni et al. (2016) [20]. These authors show a higher hydrodynamic efficiency, i.e. a slower attenuation and a farther propagation of the jets speed with the distance from the nozzle, deriving from the more important role of inertia compared with viscosity.

2.5. Mechanical properties of jet grouted material

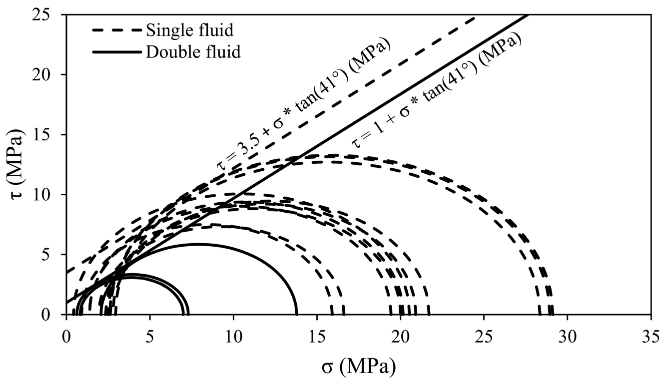
Six months after making jet grouting columns, after exposing the top portion of columns, core samples were extracted in various positions to quantify the strength of the jet grouted material. Diamond coring system Hilti DD500 with core bit of 1500 mm length and diameter of 110 mm was satisfactorily used for drilling columns and several samples (Fig. 6) were taken around the center of columns into the upper portion (about 2.0 m), marked with numbers and brought to the laboratory of the Silesian University of Technology.

Fig. 6. Core samples of jet grouted material from trial field in Bojszowy Nowe [19]

Experiments consisted in fourteen triaxial and sixty uniaxial compressive tests. The former, were carried out in a high pressure chamber on cylindrical samples having height and diameter equal to respectively 120 and 60 mm (h/d = 2.0) equipped with four extensometers (2 horizontal and 2 vertical (Fig. 7a). Cell pressure was varied between 0.41 and 2.92 MPa. The results, summarized in Table 3 and Fig. 7b, show a meaningful effect of the jet grouting technology. Difference between single and double fluid systems are evident both in terms of stiffness (see Young's module in Table 3) or strength. With regard to the latter issue, the failure envelopes traced for single and double fluid show a similar dependency of the shear strength on normal stress (a friction angle of 41° can be inferred for both systems), but a markedly different role of cementation (with cohesion equal to 3.5 MPa for single, 1 MPa for double fluid).

Cylindrical samples with height and diameter equal to 200 and 100 mm (h/d = 2.0) and equal to 100 and 100 mm (h/d = 1.0) were also cored for evaluating the uniaxial compressive strength. To avoid any changes in the results, all samples were stored and prepared using the same procedures. Top and bottom faces of all samples were flattened by filling with sand in order to create parallel and smooth bases for strength tests (Fig. 8), then samples underwent uniaxial compression in a testing machine carried out with 1 or 2 kN/s load speed. For each sample stress-strain curved was obtained. Based on these characteristics, Young's module E and Poisson's ratio ν were obtained (see Table 3).

(a)



(b)

Fig. 7. High pressure triaxial device and sample of jet grouting material equipped with extensometers [19] (a), failure envelope for single and double fluid jet grouting (b)

Fig. 8. Cylindrical samples of jet grouted material prepared for uniaxial compressive tests [19]

Table 3. Summary of triaxial test results on samples cored from jet grouting columns

No.	Column	Depth [m]	Cell pressure σ_3 [MPa]	Young's module E [GPa]	Poisson's ratio ν [–]	Maximum deviator stress $(\sigma_1 - \sigma_3)$ max [MPa]
1	S6	0.00÷0.40	2.92	2.91	0.12	25.43
2	S6	0.00÷0.40	2.57	3.82	0.19	26.55
3	S1	0.60÷1.25	2.76	3.63	0.15	18.95
4	S5	1.90÷2.40	1.93	3.13	0.40	14.68
5	D8/0.5R	0.00÷0.40	0.61	0.92	0.21	6.69
6	S4	0.60÷1.60	0.89	6.53	0.12	15.02
7	S4	0.60÷1.60	2.48	5.24	0.13	18.44
8	S4	0.60÷1.60	1.37	5.86	0.09	18.79
9	S7	2.35÷3.40	2.34	3.75	0.27	17.67
10	S7	2.35÷3.40	0.41	6.07	0.12	20.13
11	D4/0.5R	0.00÷0.40	2.06	0.88	0.20	11.72
12	D4/0.5R	0.00÷0.40	0.81	1.37	0.16	6.19
13	S8	0.80÷1.65	1.36	3.94	0.11	18.07
14	S8	0.80÷1.65	2.61	5.48	0.17	26.33

The mean strengths are summarized in Table 4 distinguishing the results obtained with single and double fluid jet grouting and grouping them for the different sample shape ($h/d = 1$ or 2) and loading speed ($L_s = 1$ or 2 kN/s).

Table 4. Summary results of the uniaxial compressive strength of jet grouted material

Type of samples	Single fluid system (SF)		Double fluid system (DF)	
	No. of samples [–]	q^*_{umSF} [MPa]	No. of samples [–]	q^*_{umDF} [MPa]
1a. Load speed = 1 kN/s ($h/d = 2.0$)	14	7.1	–	–
1b. Load speed = 2 kN/s ($h/d = 2.0$)	19	12.1	8	1.1
1c. Load speed = 2 kN/s ($h/d = 1.0$)	27	9.2	19	2.3

Interestingly, the paramount factor for strength of jet grouting material is again the injection system. In fact, with the same load speed of 2 kN/s, the uniaxial compressive strength obtained on $h/d = 2$ samples is equal to 12.1 MPa for single fluid and 1.1 MPa for double fluid system, the strength obtained on $h/d = 1$ samples is equal to 9.2 MPa for single fluid and 2.3 MPa for double fluid system. The influence of load speed is also somehow relevant, being strength higher for larger loading speeds, in accordance with several experimental observation on concrete (e.g. [25]). This evidence led to treat separately the results obtained with loading rates equal to 1 or 2 kN/s in the next analysis.

On the other hand, the influence of sample slenderness h/d seems not so important, being the values obtained with $h/d = 2$ higher than those obtained with $h/d = 1$ for single fluid, while the opposite outcome is seen for double fluid. These results suggest considering uniaxial compressive strength of the jet grouted material not much affected by the slenderness ratio (h/d) of the sample.

In order to explain the observed differences and infer the role of technology, the uniaxial compressive strength obtained on each sample has been related to the amount of cement injected per unit volume of the corresponding column. The latter has been computed dividing the amount of injected cement times the column's volume in the portion from 0.8 to 1.3 m depth, where diameter can be assumed approximately constant (see Fig. 3). The results plotted in Fig. 9 clearly show that strength is related to the amount of injected cement [26]. Considering the similarity between the parameters given for grout injection in single and double fluid systems (see Table 5), which turns into similar amount of cement

Table 5. Technological parameters of tested jet grouting columns compared to average diameter, cement per unit volume and uniaxial compressive strength of jet grouted material

No. of column	No. of nozzle M [–] and its diameter d_{01}, d_{02} [mm]	Grout pressure p_g [bar]	Grout flow rate [l/min]	Average lifting speed V_s [mm/s]	Average diameter [m]	Rotation speed of the monitor Ω [rpm]	Cement per unit volume [kg/m^3]	Uniaxial compressive strength [MPa]
1S	2×4.0	360	316	8.30	1.13	25	475	7.3
2S	2×2.8	360	155	8.30	0.94	25	337	3.8
3S	2×4.0	180	233	8.30	0.90	25	528	15.3
4S	2×2.8	250	129	8.30	0.78	25	407	8.4
5S	2×4.0	360	316	8.30	1.13	12	475	7.4
6S	2×2.8	360	155	8.30	0.98	12	310	9.1
7S	2×4.0	180	223	8.30	0.90	12	528	13.0
8S	2×2.8	250	129	8.30	0.86	12	335	8.8
1D	2×4.0	360	316	8.30	1.75	25	198	1.5
2D	2×4.0	180	223	4.15	1.61	25	330	1.2
3D	2×4.0	360	316	8.30	1.73	12	203	2.8
4D	2×4.0	180	223	4.15	1.58	12	343	1.9
5D	2×2.8	360	155	8.30	1.54	25	125	1.9
6D	2×2.8	260	131	8.30	–	25	–	1.2
7D	2×2.8	360	155	4.15	1.88	12	168	2.1
8D	2×2.8	250	129	4.15	1.63	12	186	0.9

injected for unit length of the column, the lower density of cement derives from the larger dimension of columns obtained with double fluid system. In other words, double fluid system tends to diffuse the injected cement over larger soil volumes and this occurrence is responsible for a weaker cemented material. In addition, the presence of air injected with double fluid system tends to speed up cement carbonation as shown in [27] and this effect contributes to produce a lower material strength.

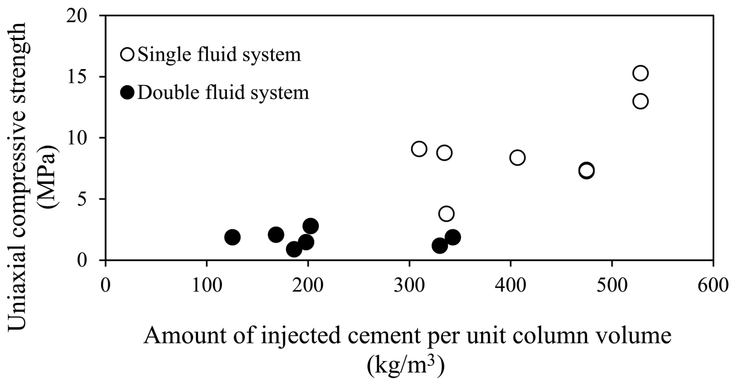


Fig. 9. Uniaxial compressive strength as function of the cement injected in the unit volume of column

3. Conclusions

In spite of a large popularity of jet grouting, there are still fundamental uncertainties on the role of the executive factors on the final product. Among the most relevant questions is a realistic estimation of the columns dimension and mechanical properties in relation with the injection system and parameters. Improving the predictive capability would make the technology more profitable, optimize design and execution reducing the current redundancy of treatments, make solutions safer, cost effective, environmental-friendly and convenient.

The experimental campaign herein carried out, specifically aimed at investigating the role of technological factors, has shown that larger diameters are obtained with double fluid system, confirming the positive role of the shrouding compressed air jet. The comparison with values predicted with a formula previously developed by authors reveals that the role of all factors can be satisfactorily summarized into the specific energy at the nozzles. Prediction is extremely good for single fluid (the mean absolute error MAE is equal to 2.4%), less appealing for double fluid with an underestimate of diameter (MAE = 10%). A correction of the formula, changing the specific energy exponent β from 0.2 to 0.24, has enabled to capture the role of higher energy and reduce MAE to 3.0%.

On the opposite hand, the increase of diameter produced by air in double fluid system turns into a reduction of the material strength. This result has been repeatedly observed on triaxial tests and uniaxial compressive tests. Interestingly, the failure envelopes obtained from triaxial tests revealed a similar dependency of the shear strength on the normal stress (friction angle was in both case equal to 41°), a stronger cementation on single than on double fluid columns, with cohesion respectively equal to 3.5 and 1 MPa. Similar conclusions can be drawn from the large number of uniaxial compressive tests. With regard to strength, the role of technological factors can be summarized by the amount of cement injected per unit column's volume. This variable enables to explain the difference between single and double fluid, considering that the similar amount of cement injected per unit column's length is diffused on larger cross section in the case of double fluid system.

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Analiza wpływu parametrów technologicznych iniekcji strumieniowej na właściwosci kolumn na podstawie pełnowymiarowych badań terenowych

Słowa kluczowe: jet grouting, system pojedynczy, system podwójny, badania terenowe, przewidywanie geometrii kolumn iniekcyjnych jet grouting

Streszczenie:

Technika iniekcji strumieniowej jest procesem wykorzystującym efekt przecinania i rozdrabniania gruntu pod działaniem strumienia zaczynu cementowego iniekowanego do gruntu. Ze wzgledu na złożoność procesu technologicznego istnieje potrzeba wyjaśnienia zjawiska zarówno na poziomie teoretycznym, jak również przeprowadzając pełnoskalowe badania eksperymentalne.

W artykule przedstawiono wyniki badań terenowych wykonanych na przygotowanym poletku doświadczalnym. Szczególną uwagę zwrócono na rolę zmiennych parametrów technologicznych na właściwości geometryczne i mechaniczne kolumn iniekcyjnych. W tym celu wykonano 16 kolumn iniekcyjnych: 8 w systemie pojedynczym i 8 w systemie podwójnym. Kolumny, o długosci 4 m każda, formowane były różnicując system iniekcji oraz parametry technologiczne: ciśnienie iniekcji, średnicę dysz iniekcyjnych oraz prędkość obrotową żerdzi iniekcyjnej. Następnie zostały one odsłonięte, oczyszczone i zinwentaryzowane. Dodatkowo z kolumn pobrane zostały rdzenie celem wykonania badań wytrzymałościowych. Artykuł przedstawia podsumowanie wyników badań eksperymentalnych porównując je z wartościami uzyskanymi na drodze przewidywań analitycznych.

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