Engineering assessment of jet-grouted structures

Valoration technique des structures en sol traitées par jet grouting

M. Arroyo & A. Gens
Department of Geotechnical Engineering & Geosciences, UPC, Barcelona, Spain

ABSTRACT

The treatment characteristics, quality control measures and outcomes of two different jet-grout based soil treatments are described in detail. In the first one, a jet-grouted slab was built to limit retaining wall movements in a cut-and-cover tunnel. Quality control relied on borehole core quality assessment and laboratory testing. Core quality was very sensitive to coring practices. The strength and stiffness of the jet-grouted slab were deemed adequate and the structure successfully contributed to minimal wall movements. In the second case, a jet-grouted treatment was designed to provide strengthening and impermeabilization around a tunnel excavated on silty sands below the water table and underneath another tunnel. Control was based on extensive coring, cross-hole seismic surveys and permeability tests. The results were generally favourable and where defects were detected, reparation was undertaken. However, in spite of all those actions, a number of deficiencies escaped detection and only became apparent during the excavation of the tunnel resulting in significant construction problems.

RÉSUMÉ

Les caractéristiques de traitements, les mesures de contrôle de qualité et les résultats de deux différents traitements de sol par jet grouting sont expliqués en détail. Dans l'un d'entre eux, on a construit une plaque par jet grouting pour limiter les mouvements des parois de soutènement d'une tranchée recouverte. Le contrôle de qualité s'appuyait sur l'évaluation de la qualité des carottes de sondage et des tests de laboratoire. La qualité des carottes était très sensible à la méthodologie de forage. La résistance et la rigidité de la plaque par jet grouting ont été considérées adéquates et la structure a contribué avec succès à limiter les mouvements de parois. Dans l'autre cas, un traitement par jet grouting a été conçu pour renforcer et imperméabiliser la zone autour d'un tunnel excavé dans des sables limoneux plus bas que le niveau phréatique et en-dessous d'un autre tunnel. Le contrôle était basé sur de nombreux forages, de la sismique cross-hole et des tests de perméabilité. Les résultats étaient généralement favorables et les défauts détectés ont été réparés. Malgré tous ces efforts, un certain nombre d'imperfections ont échappé à la détection et sont seulement devenus apparents lors de l'excavation du tunnel ce qui a produit des problèmes de construction significatifs.

Keywords :

1 INTRODUCTION

Jet-grouting techniques are one of the most frequently employed means of ground improvement in difficult geotechnical situations. Almost all soils are amenable to a treatment that generally results on improved strength, improved stiffness and reduced permeability. However, it is notably difficult to assess ex-post the actual specific improvement that might be ascribed to a certain jet-grouted treatment (e.g. Puppala & Porbaha, 2004).

Although a variety of quality control techniques are available (soundings, laboratory tests, geophysics, in-situ tests) their results are sometimes ambiguous or insufficient to exclude the possibility of a local failure. This situation has different consequences according to the characteristics of the jet-grouted structure. In some cases, a treatment successful on average is perfectly fit for its intended purpose, whereas in others the treatment is only as good as the weakest element in it.

The first situation will be here exemplified by the case of a reinforced-soil slab, acting as an underground prop in a deep excavation. The second case by that of a tunnel excavated within jet grouted silty sands, below the water table and below an existing tunnel.

2 SITE A: UNDERGROUND SLAB

2.1 *Site description and treatment design*

The underground pre-formed slab is an increasingly popular means of restraining the movements associated with deep excavations, particularly in soft soils (e.g. Hsieh et al., 2003). In the case here described, the close proximity (2 m) of a 14-storey building to a 20-m deep cut and cover excavation caused some concern. The soil profile involved made ground (2 m), medium hard clays and sands, with the water table at 12 m below ground level.

The soils treated were stiff to very stiff clays (design s_u about 100 kPa at 20-25 m depth) of Pleistocene age. The need for treatment was established on the basis of a finite element analysis in which an elasto-plastic Mohr-Coulomb model was employed for lack of better soil data. From the analysis, the estimated movement of the nearby building was deemed excessive without soil treatment (up to 50 mm at the building façade), but reduced to 8 mm after treatment. The treatment was designed as a continuous slab of 4 m thickness, beneath maximum excavation level. The treated soil characteristics in the analysis were specified as 400 kPa undrained strength and 200 MPa elastic modulus. A characteristic value of unconfined compressive strength of 0.8 MPa was set as a target for the treatment.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2338

2.2 *Treatment execution*

To materialize the soil treatment a bi-fluid jet-grout technique, commercialized under the name "superjet" was proposed by the specialist contractor. The plan layout, illustrated in Figure 1, had 115 columns of estimated diameter 2.4 m located on a square grid of 1.95 m x 2.10 m. The known basic treatment parameters are collected in Table 1. As indicated, some of these parameters were verified by systematic monitoring of the injection process.

Table 1. Jet grout parameters for the cases described

PARAMETER	SITE A	SITE B	SITE B
Type	bi-fluid grout-air	bi-fluid grout-air	bi-fluid grout-air
column diameter (m)	2.4*	2	3
nozzle diameter (m)	> 0.0047		
water/cement	>1		
grout pressure (MPa)	35**	43	43
grout flow rate (l/s)	5**	5.33	5.33
lifting speed (m/s)	0.0016**	0.0018	0.0013
rotation speed (rpm)	5-6**	5	5

* Design target
** Monitoring result

2.3 *Treatment control*

Post-construction treatment control was based on soundings and laboratory testing of recovered samples. A total of 10 soundings were initially considered necessary, and three more were added later. The layout of these soundings is visible in Figure 1; it can be observed that they were located both at the column axis and at column intersections.

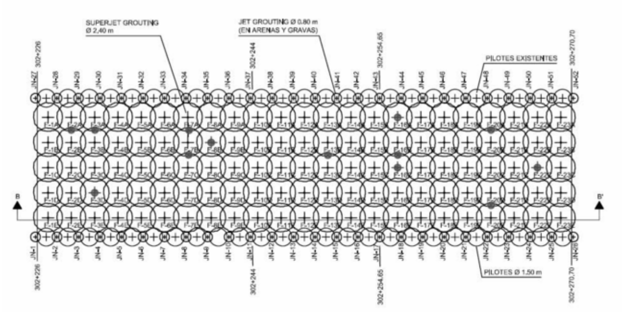

Figure 1. Layout of treatment and control soundings at site A

Core quality was evaluated using two different indices: average RQD and the core improvement rate, CIR, specifically developed by Yoshitake et al. (2004) for jet-grout evaluation. The results obtained for the 13 soundings are collected in Table 2. Alongside the column explored (where two names indicate an intersection sounding), RQD and CRI, Table 2 includes also the estimated curing time of each core before recovery was attempted and a label indicates the crew that manned the operation.

All cores were recovered were of 100 mm diameter. Crew A, initially in charge of the sounding campaign, generally employed a single-barrel coring tool with air circulation for debris evacuation. On the other hand, crew B, systematically employed a double-barrel coring tool, using water to flush out the debris. Crew B had longer experience in coring jet-grouted bodies than crew A.

Table 2. Core quality results for Site A

Column	Crew	Curing, days	CIR, %	RQD, %
22C	A	52	100	80
20D-20E	A	48	90	75
16C	A	60	0	30
16B-16C	A	61	15	45.5
16A	A	62	100	40
13B-13C	A	48	80	73
2A-2B	A	55	0	25
8B	A	55	100	13
7B-7C	A	50	0	0
3D	A	61	5	37
20A-20B	B	81	100	95
7A-7B	B	74	100	97
3A-3B	B	74	100	100

From the results obtained it was clear that crew A was using a drilling practice that damaged the cores, resulting in apparently poorer treatment quality. That was made even clearer when detailed inspection of the coring logs revealed that quality increased systematically when crew A switched from their favorite single-barrel tool to the double-barrel one. Curing time of the columns was long enough for not having had significant influence on the results.

It was interesting to note that the CRI results were less ambiguous than RQD and clustered at both extremes of the scale (Figure 2). Finally, it should be mentioned that the poor recovery of crew A largely diminished the expected amount of samples available for laboratory testing. Only seven samples were finally tested but the worst result recorded was more than three times larger than the target characteristic UCS.

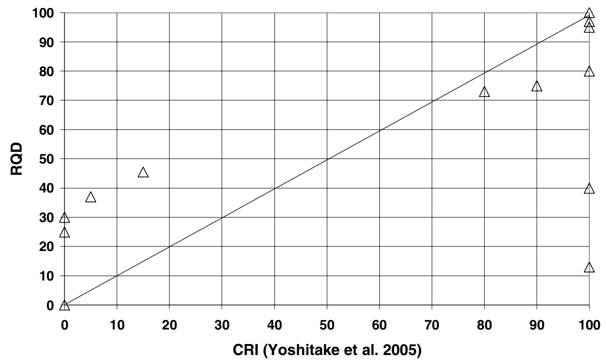

Figure 2. Qualitative evaluations of jet grout cores at site A

2.4 *Engineering assessment and treatment outcomes*

Based on the above considerations the treatment was deemed fit for purpose, and the results with low Yoshitake index were attributed to poor boring practice. Excavation was given the go-ahead.

Monitoring revealed a maximum settlement after the end of construction of 6 mm at a distance of 7 m from the wall. Perhaps serendipitously, this was in very good agreement with the numerical prediction.

3 SITE B: TUNNEL IMPERMEABILIZATION

3.1 *Site description and treatment design*

Site B was located at less than 2 km from site A, but the geotechnical setting was very different. A tunnel linking two cut and cover excavations had to cross underneath an existing railway tunnel. The new tunnel countervault was at about 23 m below ground (Figure 3). The soil profile at site B comprised 2 m of made ground, 3 m of medium clay, 8 m of medium sand, 15 m of fine sand and silts and 1 m of gravels, overbearing the same stiff clays treated at site A. The water table was at the countervault level of the existing tunnel. The newer tunnel had to be excavated through the water bearing fine sands and silts.

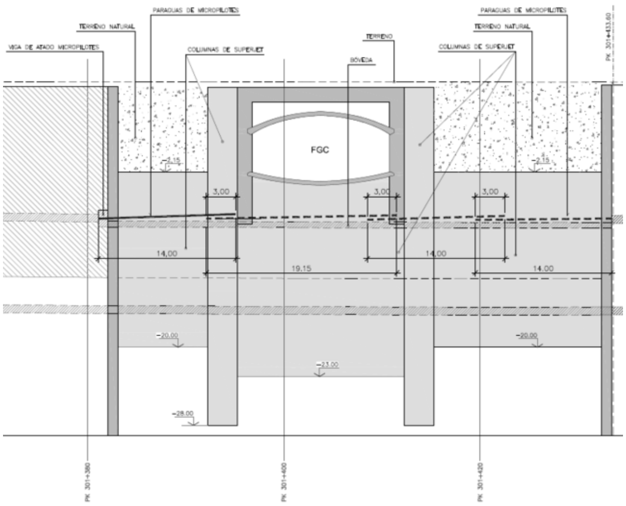

Figure 3. Designed treatment at site B: section

Apart from other protective measures the new tunnel design was heavily reliant on a jet-grouted treatment. The treatment was organized according to two main ideas: a sealing barrier around the excavation, and a generalized reinforcement inside the excavated area. The sealing barrier was partly formed by long jet-grout columns and, outside the older tunnel shadow, partly by diaphragm walls. Thus three independent enclosures were theoretically formed, one at each side of the older tunnel, and another just below it (Figure 4). Sealing was to be achieved by reaching into the clay substrate.

The columns intended for generalized reinforcement were shorter and did not seek the underlying clays.

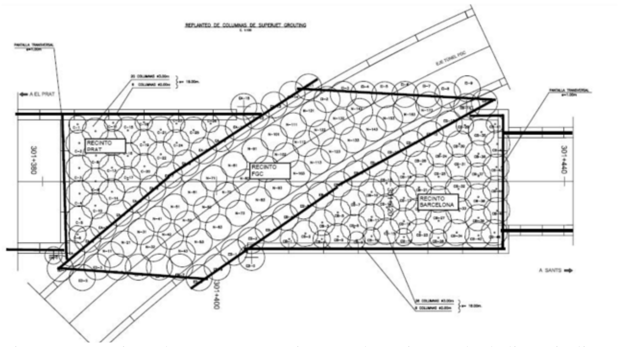

Figure 4. Designed treatment at site B: plan view. Black lines indicate sealing barriers: either diaphragm walls or long jet-grout columns

The structural design of the tunnel called for a minimum jet unconfined compressive resistance. Such resistance was specified according to the different treated layers, calling for less resistance in the fine-grained layers than in the granular ones.

3.2 *Treatment execution*

To materialize the soil treatment a bi-fluid jet-grout technique, commercialized under the name "superjet" was proposed by the specialist contractor. Two different types of columns were proposed, with 2 and 3 m estimated diameter. The plan arrangement of the columns is shown in Figure 4. The known basic treatment parameters are collected in Table 1. As indicated, some of these parameters were verified by monitoring of the injection process.

In the area under the shadow of the existing tunnel the window of opportunity for treatment execution was very limited. Therefore the reinforcement columns within the sealed area were of the larger size (3 m) and not always overlapping. The hurried execution of that area of the treatment meant that a full monitoring protocol had not been established and monitoring results were only partially available.

There was some concern about the structural state of the existing tunnel and therefore the columns below the tunnel were left a few meters below its countervault. The concerns were proven right when one column executed at one corner between the existing tunnel and the new wall damaged the existing walls.

3.3 *Treatment control*

The control plan included several items. On the one hand 17 boreholes were performed for the direct inspection of the treatment outcomes. There were only 102 columns outside the tunnel shadow, thus the rate of direct inspection was fairly intense. The borehole layout is shown in Figure 5.

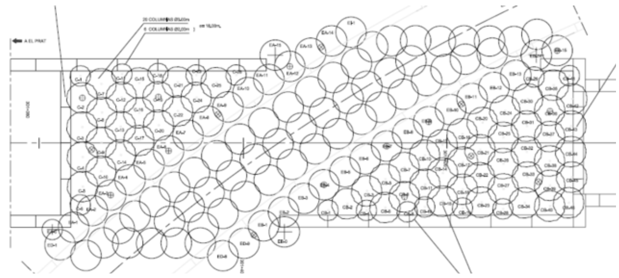

Figure 5. Inspection borehole layout

Samples taken from the boreholes were tested at the laboratory. The boreholes were also used to perform Lefranc-type permeability tests and, systematically, cross-hole seismic P and S wave measurements. Finally, three pumping tests were planned inside the accessible enclosures –i.e. those not shadowed by the existing tunnel.

Laboratory tests on the recovered samples showed a profile of UCS that, to a certain extent, mimicked that of cone resistance at the site. The values measured were well above those required. It was interesting to note that there was a clear inverse relation between the void ratio of the treated soil and the UCS (Figure 6). It was noted that a large number of samples had void ratios that were well above those initially estimated for the original soils. On the basis of these results the material quality of the treated soils was deemed appropriate.

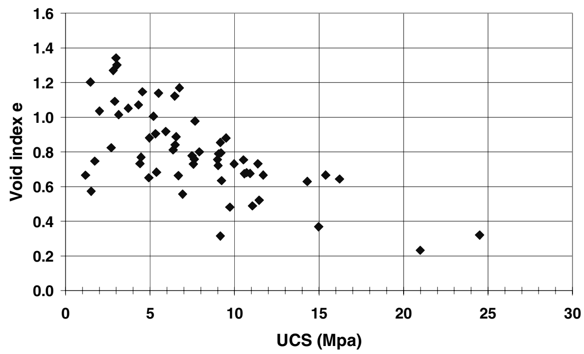

Figure 6. Site B: relationship between void index and UCS of jet-grout samples

It was far more difficult to judge about the treatment extent that had been achieved and, in particular, if the perimeter sealing of the enclosure below the active railway was properly executed.

Core improvement ratios (CIR) were above 0.80 whenever double-barrel coring was practiced. Again, single-barrel coring produced bad results in some cases. In some boreholes the bottom seal against the clay layer of the longer columns was not fully apparent. That coincided with an area in which the gravel layer just on top of the clay turned into a hardpan, with clear signs of natural cementation.

Cross-hole results were sometimes affected by borehole obstruction. This meant that alongside several paths the tests were only partially penetrating. About 25% of the 1 m spaced shots had problems in transmitting shear waves. However, whenever such failed shots were isolated, borehole sealing problems were deemed responsible. When there were several shots in series showing the same problem and different results where observed in other directions, treatment gaps were suspected. Whenever transmission was successful, the original shear wave velocity multiplied by a factor of 5 or more. The cross-hole paths were thus classified as shown in Figure 7.

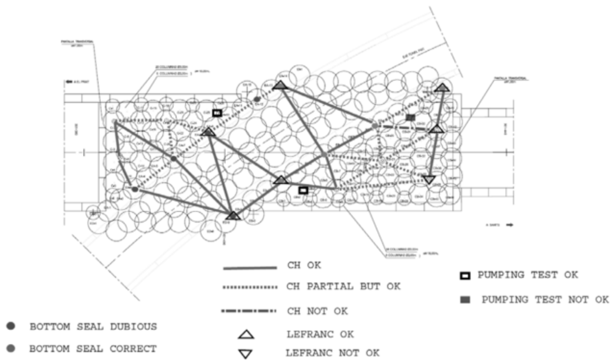

Figure 7. Locations and outcomes of cross-hole (CH), pumping and Lefranc tests, and estimation of bottom jet grouted slab state

Permeability values derived from the Lefranc tests performed in the boreholes are collected in Table 3. Tests performed in boreholes located on column axes gave lower permeabilities, as expected. However, and except for one case, were the treatment was deemed unsuitable the permeabilities were below 1E-6 cm/s.

The three pumping tests were transient-type and permeability was obtained from recovery curves. Those tests resulted in significantly higher permeability values than the Lefranc tests. Two of them gave values around 1E-4 cm/s and the third gave a permeability of 1E-3 cm/s. The latter result was taken as an indication of treatment deficiencies. The locations of the permeability measurements are indicated in Figure 7.

3.4 *Engineering assessment and treatment outcomes*

As a result of the various controls, there were significant doubts concerning several areas of the treatment and a number of repair actions were advised in the accessible areas (outside the existing tunnel shadow), before starting the excavation. the main one consisted of low-pressure grouting at a series of inter-column gaps, in the area where permeability tests and cross-hole results were unsatisfactory (Figure 8).

The repairs took place as indicated. Despite that, several incidents of water entry with soil erosion occurred when the tunnel excavation was undertaken, clearly related to treatment flaws on the closing lateral sides, below the existing railway tunnel. That was a zone that had not been directly inspected, because of access limitations. This situation led to increasingly urgent attempts to reinforce the treatment. In one of these, an improperly controlled grout injection resulted in damage to the existing railway tunnel and forced its closure.

Closure of the existing tunnel allowed a systematic repair on the area shadowed by it. The main ingredient of that repair was, again, a jet-grout treatment, trebling the thickness of the external treatment walls. Also systematic external dewatering was performed. After those operations took place the tunnel was finally excavated without further incidents.

Table 3. Permeability from Lefranc tests at site B

Column	Location	Prof, m	k, cm/s
CB33-CB39	Intercolumn	10.5	1.70E-01
CB33-CB39	Intercolumn	15.45	7.50E-02
EA8-EA9	Intercolumn	9.45	1.65E-07
EA8-EA9	Intercolumn	21.75	1.70E-06
EA13-EA14	Intercolumn	12.55	3.30E-06
EA13-EA14	Intercolumn	21.55	1.50E-06
ED9-EB1	Intercolumn	12.3	9.50E-07
ED9-EB1	Intercolumn	21.5	5.80E-07
CB19	Column axis	12	1.00E-07
CB19	Column axis	16.5	2.50E-08
CB36	Column axis	12.3	1.80E-07
CB36	Column axis	18.75	2.23E-08
EB15	Column axis	12.5	1.40E-06
EB15	Column axis	21.55	3.40E-07
EB4	Column axis	12.4	2.20E-07
EB4	Column axis	21.5	1.90E-08

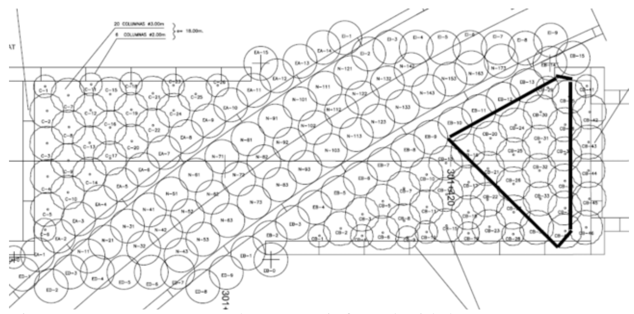

Figure 8. Treatment zone that was reinforced with low-pressure grout at inter-column gap locations

4 CONCLUSIONS

There were significant differences between the two case histories presented. Case A was inherently less risky, because its performance did not depend on local deficiencies. Case B had the added difficulty of limited access to one of the most critical zones. However, in all cases, there are inherent uncertainties in post-construction controls of local flaws in a jet-grouted mass. Treatments where the goal is very dependent in achieving certain geometric continuity clearly benefit from a redundant design. A probabilistic design framework (e.g. Croce & Modoni, 2006) is likely to prove helpful in this respect.

ACKNOWLEDGMENTS

The authors are grateful to ADIF for the opportunity given to study these cases. The work is part of the research project BIA2008-06537 funded by the Spanish Ministry of Science and Innovation.

REFERENCES

Croce P., Modoni G. (2006). Design of jet grouting cut-offs. *Ground Improvement*, 10-1, 1-9

Hsieh, H.S., Wang, C.C. y Ou, C.Y. (2003) Use of jet grouting to limit diaphragm wall displacement of a deep excavation, *ASCE J. of Geotech. Geoenv. Eng.*, 129, 2, 146-157

Puppala, A.J. & Porbaha, A. (2004) International perspectives on quality assessment of deep mixing, *ASCE Geosupport 2004*, 826-837

Yoshitake, I., Nakagawa, K., Mitsui, T., Yoshikawa, T. & Ikeda, A. (2004) An evaluation method of ground improvement by jet grouting, *Tunnelling and Underground Space Technology*, 19, 496-497