Special applications of the jet-grouting technique for underpinning works

Application spéciale de la technique de jet-grouting pour des travaux de soutènement

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ABSTRACT: For the realization of the High Speed Rail link underneath the city of Antwerp a tunnel has to be built beneath a 100 years old railway embankment containing several bridges. To reinforce the foundations of the old bridges and in order to build a new foundation at higher depth a temporary underpinning, made out of jet grout columns, was necessary. Axial loading tests were preformed with the purpose of determining the behavior of the jet grout columns. During these tests conducted on preliminary installed columns, sudden ruptures occurred in the upper section. To explain these sudden ruptures, a full-scale loading test on a column was performed in laboratory. From the results of this test it can be deduced that small heterogeneities in a grout column may have a real influence on the compressive strength of a grout column.

RÉSUMÉ: Pour la réalisation de la ligne TGV en dessous de la ville d'Anvers, un tunnel doit être construit sous un vieux remblai de chemin de fer et qui contient quelques arches. Pour consolider temporairement les vieilles fondations de ces arches et pour pouvoir construire une nouvelle fondation à plus grande profondeur, il fallait faire un ensemble des pieux de jet grouting a travers l'ancienne fondation. Lors des essais préalables de mise en charge, des phénomènes de rupture se sont produit dans la partie supérieure de quelques colonnes. Afin d'expliquer le phénomène de rupture, on a réalisé un test à vraie grandeur sur une colonne de jet grouting dans un laboratoire. De ces résultats, on peut déduire que des petites hétérogénéités dans le grout d'une colonne peuvent influencer considérablement la résistance d'une colonne entière.

1 INTRODUCTION

For the realization of the High-Speed Railway link between Brussels and Amsterdam a tunnel underneath the city of Antwerp needs to be built.

Until now the central station of Antwerp has been an end-station being used at full capacity. Since much higher capacity needs are expected in the future, an expansion of the station became indispensable. Because of the urbanised environment of the station, a subterraneous expansion under the station was designed. Underneath the station two stages are being constructed and will be accessible by a tunnel.

In the southern part of the city the tunnel has to be build beneath a 100 years old railway embankment containing several bridges. In a temporary phase the foundation of the bridges need to be underpinned. Therefore the jet-grouting technique is used.

Because the technique is used on a very large scale on this project load tests have been performed on preliminary installed columns. These tests resulted in useful information on the deformation behaviour of the columns, being installed under the old foundation of the bridge.

2 JET GROUTING TECHNIQUE USED FOR UNDERPINNING WORKS

2.1 *The underpinning works*

In order to make the excavating of the tunnel possible and to install the new foundation of the bridges at higher depth, a temporary underpinning of the old foundation of the bridges was necessary.

Some of these bridges to be underpinned have a masonry vault and are founded on a very deteriorated concrete layer. The jet grout columns also provide a consolidation of this deteriorated concrete layer.

2.2 *Jet-grouting technique*

The jet grout columns have been installed according to the mono jet system.

The preliminary installed columns were also used to verify the diameter of the columns and to optimise the installation parameters. The parameters used for the installation of the test columns are given in the first column of table 1.

During the lowering of the drilling rods water was pumped through the nozzles with a pressure of 150 bars. The drilling rods were lowered rather slowly so a hole with a diameter of about 0.30m was created before the real grouting operation was started.

With these grouting parameters the diameter of the column was about 0.60m.

The required diameter of the definitive columns under the foundation of the bridges was 0.90m. Therefore the grouting parameters had to be adapted. The used parameters for the installation of the definitive columns are given in the second column of table 1.

Table 1: Grouting parameters for the installation of 0.90m diameter grout columns

Grouting parameter	Test columns $\Phi = 0.60$m	Def. columns $\Phi = 0.90$m
The water pressure during the drilling	150bar	250bar
Nozzle diameter	1.6mm	2.8mm
Grouting pressure	450bar	500bar
Extraction speed	5sec/4cm	8.1sec/4cm
Flow	0.982l/sec.	3.170l/sec.

3 GEOLOGIC PROFILE

In table 2 the geologic profile encountered at the location of the bridges is described.

The results of a CPT-test performed in the vicinity of the bridges and the test site are given in figure 1.

Table 2: Geologic profile

Name	Soil type	Thickness m
Top layer	Quaternary Loam	3m
Formation of Berchem	Tertiary sand (40% Glauconite)	23m
Boom Clay formation	Tertiary clay	>50m

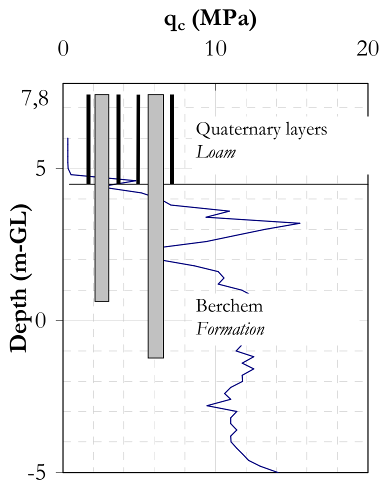

Figure 1. The CPT-test in the vicinity of the bridges and the test site

4 AXIAL LOADING TEST ON JET GROUT COLUMNS IN SITU

4.1 *Test program*

In the vicinity of the bridges to be underpinned a large number of test columns have been installed. The first aim of these test columns was to verify the accordance between the aimed column diameter the grout-strength and the used grouting parameters.

In total 6 jet-grout columns were tested with axial loading tests. The features of these columns are shown in table 3.

Table 3: Features of the tested columns

Columnnr.	$L_{Quaternary}$ m	$L_{F. of B.}$* m	L_{Totaal} m	Φ_{column} m
1	3	4	7	0.51
2	3 (Free)	6	9	0.54
3	3 (Free)	4	7	0.58
4	3 (Free)	4	7	0.62
5	3 (Free)	6	9	0.65
6	3	6	9	0.51

* : Formation of Berchem (sand)

The jet grout columns have a total length of 7 or 9 m, a diameter between 0.51 and 0.65m and are made in a two-layered soil (Figure 1). Pull out tests (Columns 1 and 6) and axial loading tests (columns 2-5) were performed on the different columns.

In order to simulate the presence of the old foundations underneath the bridge and to eliminate the friction in this part of the tested columns, a large tube was put over the first 3 m of the axially loaded columns, after the installation of the columns. The depth of 3 meters has been chosen as it corresponds to the mean foundation level of the bridges.

The tests were performed in accordance with the recommendation of the LCPC [1] (Laboratoire Central des Ponts et Chaussées). In each test the load was put on the column in 8 stages with a duration of 1 hour. During this hour the displacement at the top of the column was measured at pre-set timing. The tests were carried out until 2 time the estimated working load of the column was achieved.

4.2 *The results and interpretation of the tests*

The interpretation of the test results was done in accordance with the recommendations of the LCPC, based on the creep load

Table 4 displays the obtained working load of each column with the matching displacements. These results show a displacement of the column at working load of less than 1% of his diameter.

Since for the design of the underpinning, a design load corresponding to a stress in the grout columns of 1 MPa was considered, a settlement of about 3 mm could be expected.

Table 4: The results of the axial loading tests

Columnnr.	Type of the test	Working load kN	Displacement mm
1	Pull out test	744	4.43
2	Loading test	>1120	5.63
3	Loading test	736	3.45
4	Loading test	680	3.32
5	Loading test	>1120	5.35
6	Pull out test	>900	>5.23

The construction around the test on column 6 being too weak, the test could not be performed until maximum load.

In figure 2 the different load-displacement diagrams for the axial loading tests are shown. Figure 3 shows the load-displacement diagrams of the pull out tests.

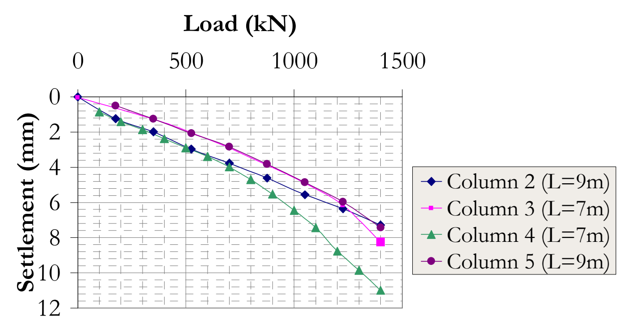

Figure 2. Load displacement diagram for axial loading tests

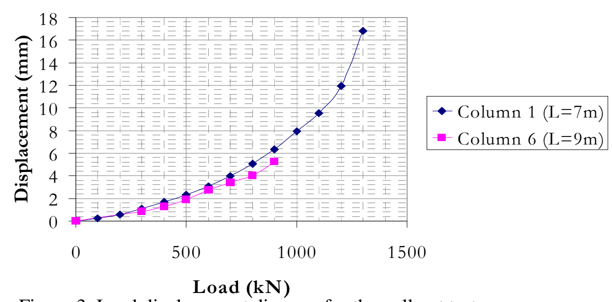

Figure 3. Load displacement diagram for the pull out test

4.3 *The behaviour of the grout columns*

To estimate the behaviour of the grout columns the load displacement diagrams were compared with the theoretical load displacement diagram given in the NEN [2]. In the NEN, depending on the pile type 3 different diagrams are distinguished. These diagrams are given in function of the ultimate load of the pile.

Since column 1 is the only test column for which the maximum load approaches the ultimate load of the column the comparison could only be done for this column. The effective ultimate load of the column was extrapolated out of the test results with the Van Der Veen method and is given in table 5.

Table 5 : Ultimate load calculated using Van Der Veen method

	Van Der Veen kN
Test column 1 (Pull out test)	1341

From the ultimate load a value of α_s can be deduced, with ultimate shaft friction of the pile $q_s = \alpha_s.q_c$ (q_c = cone resistance of CPT).

When using an average resistance of q_c in the upper layer of 3Mpa and q_c in the formation of Berchem of 9Mpa (figure 1) one can deduce an α_s –value of 0.018. This value of α_s is higher than the maximum value (α_s = 0.014) given in the NEN for displacement piles and much larger than the value (α_s=0.006) given for bored and screwed piles. This is probably due to the irregular shape of the grout column and the high pressures used to install the column.

In figure 4 the measured displacement values are compared to the theoretical load displacement diagrams (NEN) for the different type of piles. The value given in table 5 was used as ultimate load of the column.

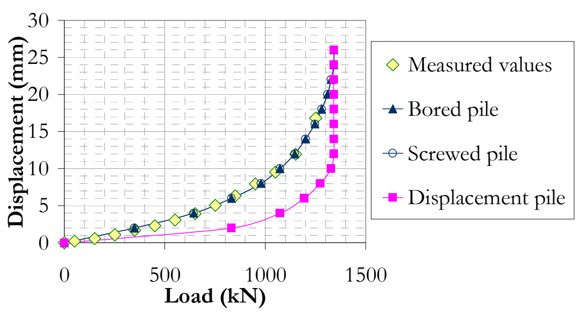

Figure 4 : Comparison of the measured load displacement values to the theoretical load displacement diagrams (NEN)

Out of this comparison and according to the load displacement diagrams, given in the NEN, one can deduce that the mobilization of the shaft friction of a grout pile is similar to the mobilization of the shaft friction of bored and screwed piles.

4.4 *Problems during the axial loading tests*

During the tests a sudden rupture in the upper section of two jet grout columns occurred when the load of 1500kN was installed. At that moment the stress in the grout column was about ±5 N/mm².

Afterwards the remains of the broken columns were transported to the laboratory Reyntjens of the University of Leuven for further investigation.

In these remains different tinctures of the grout could be observed. From the largest parts cored samples with an average height of ±100mm and an average diameter of ±112mm were cored and tested. From the tests a minimum compressive strength of the grout of ±11N/mm² could be determined.

Since the failure occurred at 45% of the min compressive strength of the grout column other reasons than a possible insufficient strength of the grout must have caused this sudden rupture of the column. For a better comprehension of the failure mechanism of this rupture a full-scale test on an excavated jet grout column had to be performed in laboratory.

5 AXIAL LOADING TEST ON AN EXCAVATED JET GROUT COLUMN IN LABORATORY

For the execution of the full-scale test in laboratory a specially made grout column was excavated about 6 weeks after its realisation and transported to the laboratory Magnel of the University of Ghent. The grout column was not reinforced with a steel bar and during transportation special care was taken to ensure the integrity of the column.

At the laboratory the column was kept under ideal conditions to avoid its drying out. Solely for the preparation of the column (2 days before performance of the test) the column was placed in the laboratory under normal conditions and so that the drying out of the column could take place. Due to this phenomenon small fissures could be observed on the surface of the grout column when the load test was performed.

At the upper part of the column about 65cm grout was removed and about 10cm at the bottom. In order to obtain flat surfaces about 10cm of concrete was installed at both ends of the column. These concrete layers were slightly reinforced. In this way a column with a final height of 2.68m was obtained. The diameter of the column was measured at different levels. The measurements are summarised in table 6. The average diameter of the column was about 0.67m. The column was put into a hydraulic press as shown in figure 5.

The column was tested in steps of 300kN until a maximum load of 2700kN, point at which failure of the column occurred.

Table 6: Columns diameter measured at different levels

Distance from the top of the column m	Diameter m
0.45	0.60
1.35	0.71
2.00	0.63
2.60	0.71

Figure 5. Full-scale test of a jet-grout column in laboratory

Each stage was maintained for 10 minutes while the deforma-

tion of the column was constantly monitored at 4 diametric positions over the diameter of the column.

The deformation of the column was measured over a height of 2m. These measurements were taken with an accuracy of 0.01mm and are shown in figure 6.

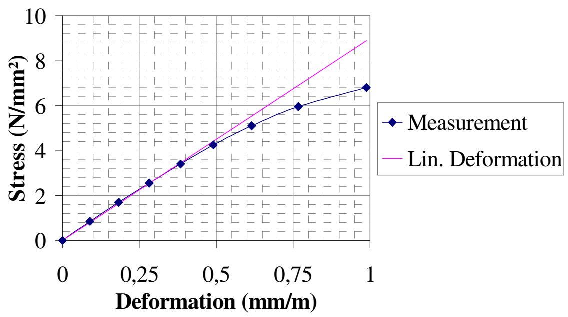

Figure 6. The deformation of the column

Within the first 30 seconds after installation of the load of 2700kN a first vertical crack at the top of the column occurred which then quickly progressed until failure of the whole column. Figure 7 displays the broken column.

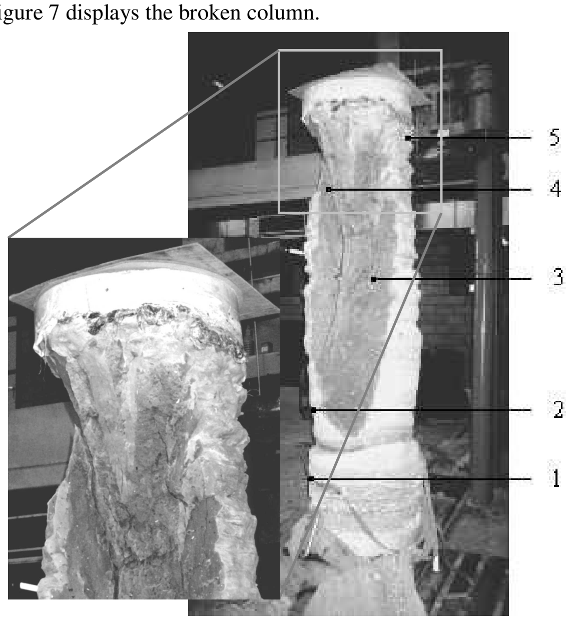

Figure 7. The grout column after testing

One can observe that failure occurred at the column head, and that probably an already existing conical surface in the grout column introduced the rupture.

From this observation it can be concluded that during the loading of the column the conical shaped upper part was pushed into the lower part of the grout column. In this way very high tensile stresses are introduced in the column. This also explains the appearance of vertically fissures in the upper part of the column before rupture took place.

At the surface of the conical shaped upper part a thin sand layer (± 3 mm) could be observed. The presence of this thin sand layer is inherent to the installation method of the grout columns.

After installation of the grout column and during the hardening of the grout a decantation of the grout takes place. This is a well known phenomenon that is more pronounced as the grout columns are installed in a sandy layer with a relatively low water level. As a result of this phenomenon a lowering of the grout surface takes place during the hardening period of the grout, and a conical shaped void arises in the upper part of the column. Filling up of this void is normally done in several phases, with the same grout as used for the installation of the grout columns (w/c ratio of about 1/1). Between each phase a thin sandy layer can occur and may be, for instance, due to the inflow of drilling fluid during the installation of a grout column in the same area. A detail of the hard cone under the upper plinth of column is given in figure 7.

When the load test was completed core samples were taken from the column at the five levels indicated in figure 7. At each level three samples, two at the edge and one in the middle of the column were tested. The samples had an average diameter of 64.3mm and an average height of 57.2mm.

In Table 7 the compressive strength of the samples are summarised.

Table 7: The compressive strength of the samples at different levels in the column

Level nr.	Distance from top	Compressive strength		
	m	Left N/mm²	Middle N/mm²	Right N/mm²
1	2.32	33.00	13.60	24.10
2	1.78	35.30	23.60	23.80
3	1.18	19.40	7.00	-
4	0.83	13.90	15.80	24.90
5	0.32	17.50	15.80	20.30

Out of these results a wide variety of the compressive strength of the grout, which increases in the upper part of the column, can be deduced. Furthermore the strength of the grout in the centre of the column is always smaller than the strength in the other part of the column. The smallest compressive strength was about 7N/mm² where the rupture of the column occurred at a main stress of 7.60N/mm².

As for the failure mechanism we can say that the column behaves as a unit as long as there are no fissures in the exterior skin of the column.

From the results of the deformation of the column (figure 7) a deformation modulus of the grout column was deduced of 8990N/mm².

6 CONCLUSION AND TOPICS FOR FURTHER INVESTIGATION

The execution of loading tests gives useful information on the behaviour of the grout columns

From the results of the pull out test (column 1) it can be deduced that the shaft friction of the grout column is similar or even higher than the one calculated for displacement piles according to the NEN. The displacement necessary to mobilise the shaft friction corresponds more or less to the one whom is normally considered for bored piles. The displacements of the load tests are not large enough to allow conclusions convening the mobilisation of the base resistance.

From the result of the full scale test in laboratory one can deduct that a small heterogeneity in a grout column, introduced during the execution of the grout column, may have a real impact on the compressive strength of the column. So the question has to be put forward if it is really possible to determine the compressive strength of a grout column from the compressive strengths measured on cored cylinders having small diameters.

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