Conference Paper, Author's Postprint

Pohl, Martin; Abratis, Joachim; Peschken, Gabriele

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Erstveröffentlichung in Australian Geomechanics Socitety (Hg.) (2022): Proceedings of 20th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE 2022). Sydney, Australia, S. 4157-4162.

Jet grouted tie-back piles at high loads in an aggressive soil environment

Martin Pohl[a], Joachim Abratis[b], Gabriele Peschken[c]

[a] Federal Waterways Engineering and Research Institute, Germany

[b] Federal Waterways and Shipping Administration, Brunsbuettel, Germany

[c] Federal Ministry of Transport and Digital Infrastructure, Germany

Abstract: At Europe´s currently largest hydraulic engineering construction site, the 5th lock chamber in Brunsbuettel (Germany), so-called jet grouted piles are used to anchor back the lock chamber walls and lock base. The use of these elements became necessary for several reasons: in the vicinity of the existing locks, which are over 100 years old, pile driving is not permitted, groundwater that is aggressive to concrete (ammonium and sulphate) occurs in relevant proportions in the load transfer area and comparatively high loads of up to 2600 kN must be transferred. The piles consist of a jet grouted column with a diameter of 1.0 m and lengths up to 7.5 m, into which a thread bar (diameter up to 14 cm) is inserted. As there is no general approval by the building authorities for such jet grouted piles, an individual approval was granted after extensive investigations and theoretical considerations. The jet grouted piles were chosen because the jet grouting of the subsoil creates an interlocking of the jet grout column with the subsoil due to different erosion resistances. In addition, when using a cement with a low w/c-value of 0.6, a permanent load transfer is guaranteed, even if the concrete is attacked. The jet grouted piles are used at depths from 25 m below ground level (in the load-bearing sands).

Keywords: back-ties; jet grouted pile; lock; concrete corrosion; ammonium

Pieux injectés par jet grouting et ancrés en arrière, soumis à des charges élevées dans un environnement de sol agressif

Résumé: *Sur le plus grand chantier actuel de génie hydraulique d'Europe, le 5e sas d'écluse de Brunsbuettel (Allemagne), des pieux injectés (« jet grouted piles ») sont utilisés pour ancrer les murs et le fond du sas. L'application de ces éléments est devenue nécessaire pour plusieurs raisons : à proximité des écluses existantes, qui ont plus de 100 ans, le battage de pieux n'est pas autorisé ; les eaux souterraines qui sont agressives pour le béton (ammonium et sulfate) sont présentes dans des proportions importantes dans la zone de transfert de charge, et des charges relativement élevées allant jusqu'à 2600 kN doivent être transférées. Les pieux sont constitués d'une colonne injectée d'un diamètre de 1,0 m et de longueurs allant jusqu'à 7,5 m, dans laquelle est insérée une tige filetée (diamètre jusqu'à 14 cm). Comme il n'existe pas d'autorisation généralisée de ce type de pieux injectés par les autorités de construction, une autorisation individuelle a été accordée, après des recherches approfondies et des considérations théoriques. L'injection par « jet grouting » a été retenue, cette technique favorisant*

l'emboîtement de la colonne injectée avec le sous-sol en raison des différentes résistances à l'érosion. De plus, avec un ciment d'une faible valeur eau/ciment de 0,6, un transfert de charge permanent est garanti, même si le béton est corrodé. Les pieux injectés sont utilisés à des profondeurs supérieures ou égales à 25 m sous le niveau du sol (dans les sables porteurs).

1 Introduction

The Kiel Canal crosses Germany's northernmost federal state for almost 100 km and connects the North Sea with the Baltic Sea for seagoing vessels. The Canal is considered to be the busiest artificial waterway in the world. Fluctuations in water levels between the Canal and the North Sea (Elbe) or the Baltic Sea (Kiel Fjord) are compensated for navigation by locks at Brunsbuettel and Kiel-Holtenau. At both locations the lock systems consist of a "small double lock" and a "large double lock". The Kiel Canal and the small locks were put into operation in 1895 after eight years of construction. The first extension of the Kiel Canal was carried out between 1907 and 1914, during which time the large locks were also built. The lock have been in continuous operation ever since.

The small locks in Brunsbuettel were renovated on the 1980s. After more than 100 years of use, the large locks also require a basic overhaul of the solid construction, hydraulic steelwork and the mechanical and electrical installations to maintain traffic and operational safety.

Due to the nature of the necessary restoration work, this would inevitably result in closed periods for shipping, which were judged to be intolerable. In order not to restrict the availability of locks, it is therefore necessary to build another large lock chamber, the so-called 5th chamber, so that shipping can always use two large locks. For the location of the 5th chamber, different variants were examined, Aspects such as nautics, property boundaries and existing buildings were used as criteria. The cost-benefit analysis showed that the highest utility value would be achieved by a basic overhaul of the large lock subsequent to the construction of a new 5th lock chamber on the lock island, i.e. between the large lock in the north (Fig. 1, left) and the small lock in the south (Fig. 1, right).

2 Subsoil

To explore the subsoil, around 2100 meters of soil samples were drilled and comprehensively examined in the geotechnical laboratory. The subsoil structure in the area of the Brunsbuettel lock is characterized by glacial deposits at depths from about 35 m below ground level and more recent deposits above this depth as a result of post-glacial sea-level rise (Fig. 2). In concrete terms, soft marsh soil is present from ground level down to a depth of about 25 m. The soft marsh soil consists of a vertical repeating sequence of clay, silt and fine sand in different forms. This is followed by well bearing sands with gravel parts. In this soil layer there is a sequence of ice-age cohesive deposits in the form of basin clay and boulder clay; predominantly of solid to firm consistency. As a result of periglacial processes, the boulder clay is strongly worked up locally and interspersed with sand, so that small-scale changes occur.

Figure 1: Construction site of the 5th lock chamber on the lock island (year 2020).

The triaxial and oedometer tests carried out on cohesive soil samples in the laboratory are particularly noteworthy. These are necessary for the derivation of realistic soil parameters for the design of the components as well as the stress-strain-behavior for numerical simulations. A classification and detailed consideration of the test results on the soft marsh soil into sandy, silty and clayey properties made it possible to specify the soil behavior in a technically correct and economically optimized manner (Pohl & Abratis, 2020). A subdivision into sandy and clayey characteristics of the excavated material was further required for the usage at dyke protection measures. For this purpose, the soft marsh soil was investigated and evaluated according to EAK, 2002.

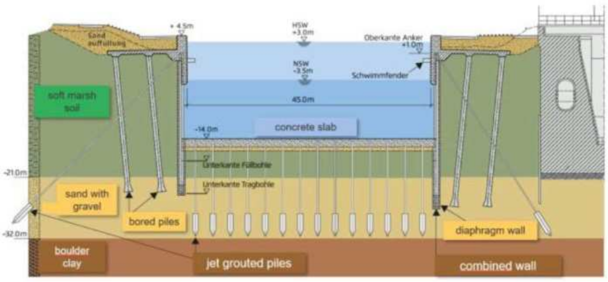

Figure 2: Cross section of lock chamber (schematic).

3 Restraints by neighbouring buildings on design and construction

Taking the subsoil into account, the effects of pile-driving vibrations were considered for the planned new construction of the 5th lock chamber. In particular, the old and structurally very sensitive locks in the immediate vicinity had to be considered, as their operation had to be guaranteed without restrictions. The investigations concluded, that only low-vibration i.e. gripping or drilling construction methods should be used in large areas of the planned 5th chamber. The installation of steel profiles by means of impact or vibration ramming was therefore ruled out.

For the wall construction, it was decided to build a sealing wall into which steel sections are inserted as a combined sheet pile wall (Fig. 2). The dimensioning of the chamber walls resulted in tie-back forces of up to 2600 kN. As only drilling methods were considered for the back-anchoring, the decision was made to produce so-called jet grouted piles. Experience with this type of back-anchoring elements is available in a figurative sense and discussed in section 5.

4 Groundwater conditions

To derive the design relevant groundwater levels, pore water pressure sensors were installed in selected boreholes. Some of them were constructed to wells with filter sections in different depths. The measured data are sent to a server, where they are processed, visualised and made available to all parties involved. The data analysis showed that the groundwater in the sands communicates with the tidal-influenced water levels in the Elbe and has similar pressure levels; while the groundwater in the soft marsh soil is dominated by meteorological events (Schulze & Pohl, 2011). A future sea-level rise of 90 cm was also taken into account.

The analysis of the groundwater chemism showed that there is a weak concrete attack (XA1 according to the German standard DIN 4030-1: 2008) by sulphate (driving attack) and ammonium (dissolving attack) at the depth of the tie-backs in the sands. The measured values are between 230 and 340 mg/l for SO_4 and between 16 and 25 mg/l for NH_4 (Figure 3). A more detailed examination also showed that the salt water influence on the Elbe side, characterized by negative base exchange indices (BEX), reduces the ammonium concentration. Hence, the excavation of the lock island at the Elbe-side will lead to a reduction of the ammonium concentration due to the inflowing salt water in the coming years.

By comparing the analysis values of the groundwater chemism at different depths in the ground, as mentioned above, it could be shown, that at a depth of 2 meters under the soft marsh soil, the concentrations of ammonium are even 5 to 10 mg/l higher than in the planned depth of the tie-backs (Pohl et al., 2020).

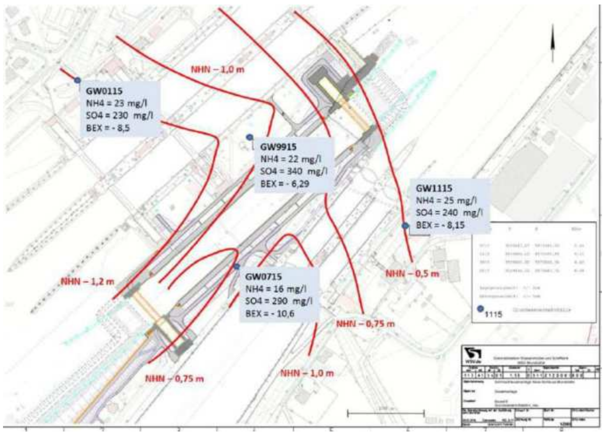

Figure 3: Groundwater contour plan with substance concentrations (statue 2015).

While the sulphate attack can be counteracted with HS cement, there are no concrete technology options for the ammonium attack. In accordance with the current state of the art, i.e. DIN 4030-1: 2008, the consequences for the back-anchoring element have been taken into account, like w/c (section 5). The given limiting values in the German standard are the same as in the standards of the UK, Netherlands, France and Belgium and have been valid since 1969. Investigations by Rechenberg & Sylla 1993, however, suggest that effects on concrete are only to be expected at much higher ammonium concentrations. Nevertheless, the conservative limiting values of the standard were applied, due to the importance of the 5th lock chamber.

5 Jet grouted tie-back piles

5.1 Jet grouting for columns and for tie-backs

In the jetting process, the soil is cut open with a cutting jet and mixed with cement; a concrete results. Apart from the water-cement content, of particular importance for the result of a jet grouted column produced in this way are the drawing and rotation speed, the pressures prevailing at the nozzle opening as well as the diameter, arrangement of the nozzle opening, and its wear (Sondermann 2012, Krentz 2015, Bergschneider 2002).

Inhomogeneities in the subsoil, such as density and grain fraction, lead to indifferent penetration depths for the cutting jet. This results in a jet grouted column with no purely cylindrical shape, but with certain indentations and projections. This characteristic is advantageous for the use of permanent back-anchoring under ammonium attack.

At “usual grouted” back-anchoring elements, the grouting pressure would drop due to the dissolving attack (Domes 2015) and the element would fail. Due to the irregular interlocking of the jet grouted column with the subsoil, a force transmission is guaranteed even with a predicted concrete corrosion zone of 1 mm per 100 years (as applies for the project presented), when achieving the characteristic properties in the jet grouted column as indicated in section 5.2.

Experiences with jet grouting as well as their usage for back-anchoring are documented in the literature. Some aspects are illustrated in the following:

In Krentz, 2015 and Kayser et al., 2007 sedimentation and other negative effects of the cement mixture of jet grouted columns are described, which were encountered and lead to a weak material strength at the top of jet grouted columns.

In bautechnik aktuell, 2000 the construction of an inclined jet grouted tie-back pile in refilled sand is presented. After drilling a cased borehole, the thread bar is positioned and the jet grouted column is constructed by pulling and rotating the casing. The nozzle is located at the base of the drilling casing. The paper shows results of a multi-stage load test of a jet grouted tie-back pile manufactured in this manner. The jet grouted column has a diameter of appr. 1.0 m and a length of 4.5 m. Forces up to 2788 kN were applied, leading to a permanent deformation of 4.8 mm. Furthermore, the paper focusses on the inner bearing capacity. By using a helix (I0xl0 mm) forces up to 3100 kN could by applied, a thread yielded 2200 kN.

Koester & Dietz describe the construction of a conventional micro-pile with a length of 10.5 m in bearing sands which has a jet grouted column at its toe over a length of 2.5 m with a diameter of appr. 1.0 m. The motivation for the jet grouted column is to encounter the concrete attack due to lime-dissolving carbonic acid. In case of the dissolving process at the micro-pile concrete, the jet grouted column should activate a passive earth pressure at the top of the column. Test loading indicated activated forces up to 1700 kN at deformations of 48 mm.

Lu et al., 2020 present pre-stressed jet grouted anchors, which were placed in silty clay. The nozzle was 2.5 mm or 2.7 mm in diameter with a cone angle of 13.5°, jet grouting pressure was 30 to 35 MPa, drilling speed of the drill rod was 8 cm/min to 10 cm/min, rotating speed was 12 r/min to 15 r/min. A jet grouting column of appr. 50 cm in diameter was constructed.

Xu, 2014 proposes jet mixed anchor piles. These anchor types have a diameter of 40-100 cm due to the higher grouting pressure compared to normal anchors. They consist of additional anchor plates in the jet grouted column and are predominantly used in soft soils, especially in silt clay. Xu describes 4 uplift-tests in mucky silt clay, where loads up to 500 kN could be applied. The corresponding displacements were 8-14 cm.

Modoni et al., 2010 show in detail the loading of jet grouted piles in dense sand. For the jet grouting a cement CEM II BS 32.SR with a grout density of 1,500 kg/m^3 was used. Injection pressure was 35 MPa, 2 nozzles with 2.5 mm in diameter and lifting speed 1.66 cm/s were used. HEB 240 steel profiles were installed in the jet grouted column. Tension forces up to 1200 kN could be applied at displacements of up to 6 cm. Bzówka, 2012 adds, that the jet grouted column has a length of 7.0 m and can be assumed to a diameter of 0.6 m.

Manassero, 2017 presents test results of inclined jet grouted tie-back anchors in loose alluvial soil with total lengths of 33 m. ln the first phase a jet grouted column with a length of 16 m and a diameter of 1.5 m is constructed. After achieving a certain strength of the column, drilling through the column followed with the installation of the anchor. The anchor consists of 29 steel strands (steel section 150 mm^2). The manufacturing parameters for the jet grouted column are given in detail to: w/c 0.83, cement III-B class 42.5, grout pressure 50 MPa, compressed air pressure 1 MPa, pulling speed 19.5 cm/min, rotation speed 12 r/min. The anchors themselves were grouted with a cement type I class 52.5, w/c 0.43. Two multi-stage load tests up to 5900 kN were carried out. The maximum displacement at this load was 78.9 mm with a permanent deformation of 13.7 mm. Additional load tests up to 4900 kN yielded permanent displacements of 8 mm.

Brengola & Roberts, 2003 use also a double rod system with grout and air for constructing jet grouted tie-backs. The jet grouted columns are constructed vertically from the surface with a length of 6.1 m and a diameter of 1.5 m, mainly in soft to stiff clay / silt. After completion of each jet grouted column 5 thread bars each of 3.5 cm in diameter were installed. In the load test up to 1335 kN, maximum displacements up to 15 mm occurred, with permanent displacements of 5 mm. Strain gages at one thread bar indicated 1300 kN of load transfer over about 5.5 m of the column. Furthermore, full length column cores were taken to confirm the column diameter and the material properties.

5.2 Construction parameters and evaluation criteria

As discussed before, jet grouted tie-back piles were planned as back anchoring elements for the 5th chamber. These consist of a jet grouted column with a diameter of 1.0 m and lengths up to 7.5 m, into which a threadbar (diameter up to 14 cm) is inserted (figure 2). It is thus a "pile" with a limited force length. As this type of back-anchoring is not common in Germany (or other countries), criteria had to be developed to guarantee a jet grouted pile with a permanently high bearing capacity for the planned service life of 100 years in the aggressive soil environment. These resulted in an "individual approval" which was issued by the Federal Ministry of Transport and Digital Infrastructure. The characteristic properties of the jet grouted tie-back piles to be produced are:

w/c = 0.6
strength class C25/30
cement content 280 kg/m^2
diameter ≥ 1.0 m.

The evaluation was based, among other things, on comprehensive tests prior to the actual construction work, in which several jet grouted columns with different equipment parameters were produced in the sands with gravel (see also Kunth et al 2014). It was necessary to prove the suitability of the jet grouting method in principle for the construction measure, because the initially planned w/c values of 0.5 are extremely low for the jetting method (Table 1).

Exploration and core drillings at the jet grouted columns as well as concrete technological investigations indicated a suitable back-anchoring element regarding the material properties under the given conditions. After a sufficient number of core drillings, the geometry, i.e. diameter of the jet grouted column, could be determined (fig. 4). As demonstrated in fig. 4 (above), the jet grouted column is of elliptical shape (dotted lines) and exceeds, for the given case, at the top the demanded diameter of 1.0 m. At the bottom of the column (fig. 4 below), the geometry is different. The contour, illustrated by the dotted line, reflects the non-steady cylindrical geometry. But also, weak material was detected, which has a negative effect on the permanent bearing capacity in respect to concrete corrosion. However, weak zones represented less than 10 % of all cone drillings, which is regarded as acceptable. One challenge was to hit the column with the drilling rod in depths larger than 25 m and to get high quality samples for the material examinations.

Of particular importance to the investigations was to prove evidence of a sharp transition between a strong concrete material of the jet column and the surrounding ground (figure 5) in order to ensure a permanent load transfer under ammonium attack. Therefore, test columns were also constructed at the same angle of 55° as the construction piles.

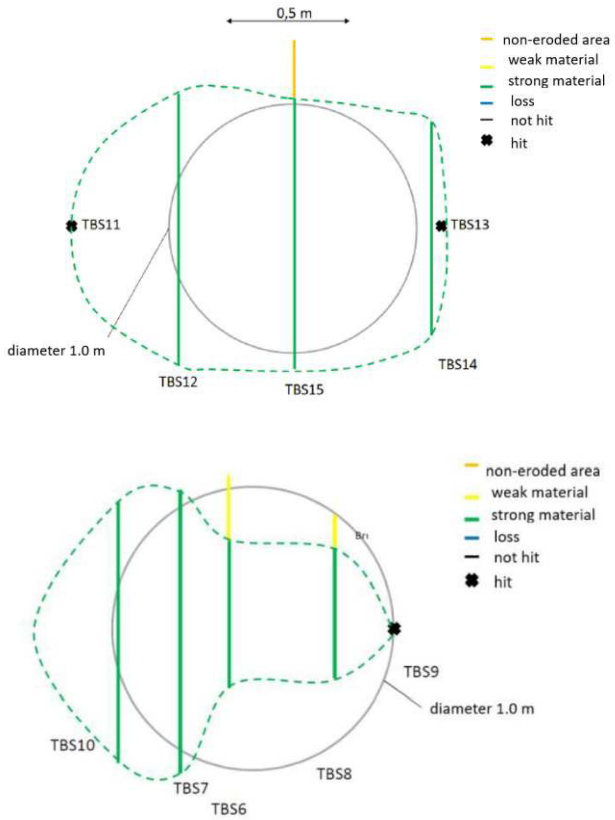

Figure 4: Determination of diameter by core drillings (above: near top of column, below: near base of column).

Figure 5: Sharp transition between the jet column and the soil.

Within the scope of the actual construction project, the manufacturing parameters for the jet piles for the equipment configuration used, were also successfully determined (Table 1). These show a clear difference from the manufacturing parameters in the preliminary tests.

The jet grouted tie-back piles are constructed in general as follows: The jetting rod system is driven to the base of the column to be constructed, then the first jetting phase starts, with the parameters given in table 1. The jetting rod is slowly pulled. This process is repeated for the second jetting phase, with the equivalent jetting parameters. In the last phase, the drilling casing is driven to the base of the column and the material inside is replaced by a cement-mixture with a w/c 0.45. Then, the thread bar is installed and the casing pulled.

By the construction process described above, blocks and gravel can sink to the base of the column and do not influence the load transfer from the soil over the column to the thread bar as well as the construction itself. Possible jetting shadows (Stein, 2004) leading to insufficient bearing capacities are excluded. By two jetting phases, the open-cut volume in the first phase is mixed in the second phase with a given cement, leading to the demanded material properties of the column and ensuring a sharp transition between jet column and soil.

Table 1: Manufacturing parameters of the jet grouted tie-back piles (load tests).

Parameter	*Preliminary tests*	*Construction work*
Nozzle diameter (mm)	2 x 4	1 x 5.5
1st jetting phase		
pressure (MPa)	40	40
w/c (-)	0.8	2.5
Pulling speed (cm/min)	20	20
Rotation speed (r/min)	10	10
2nd jetting phase		
pressure (MPa)	15	40
w/c (-)	0.5	0.8
Pulling speed (cm/min)	38	10
Rotation speed (r/min)	19	5
Examined column diameter (m)	0.95-1.1	1.0-1.4
Length (m)	5.5	4.5 / 7.0
Inclination to vertical (°)	0	37.5 / 55
Density of gravelly Sand	high to very high	moderate to very high
Diameter thread bar (mm)	130	90 / 120
Helix geometry of thread bar (mm)	14x14, s=100	14x14, s=100
Replaced cement at thread bar w/c	0.45	0.45

5.3 Load bearing behavior

In addition to the investigations discussed before, load tests were conducted at all project phases, i.e. at the preliminary tests for the feasibility and the main construction work. Due to the unusual tie-back system, quality tests (fig. 6) are conducted at 10% of all construction piles to prove evidence of the bearing capacity and a proper manufacturing.

Figure 6. quality load tests at construction piles

Figure 7 shows the load-displacement-behavior of selected jet grouted tie-back piles with construction parameters as given in table 1. The piles tested by the quality tests have varying lengths.

The maximum force applied was 4300 kN in multi-stage loading tests with one unloading cycle. Even at this high load, the permanent soil-deformations amounted only to around two centimetres, considering work piles (55°, l=7.0 m) the steel deformation accounts for 77 mm at 4300 kN, whereas the total displacement is 92 mm at this load, showing that the deformation of the tread bar governs the load-displacement-behavior of the jet grouted tie-back piles.

The load-displacement-curves on fig. 7 reflect a similar behavior of the jet grouted tie-back piles in the gravelly sands up to around 2000 kN. Then, the displacements of the shorter piles, e.g. of the quality tests, increase, whereas the longer piles show a steady linear increase of displacements.

The unloading curves reflect the elastic deflection of the thread bar, with a slight plastic soil-deformation due to the loading process.

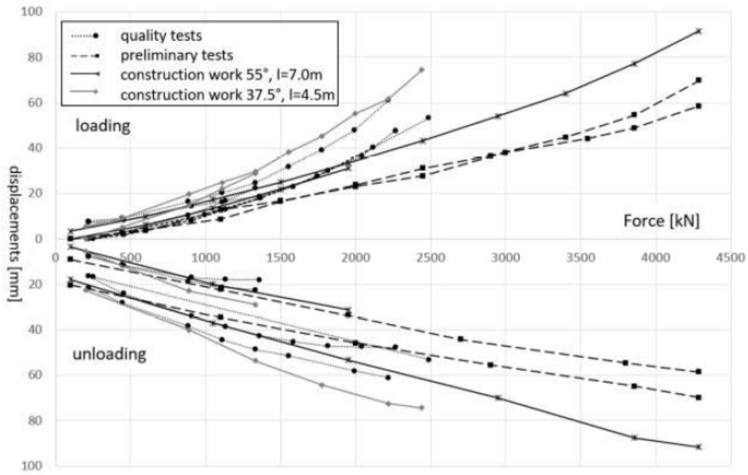

Figure 7: load-displacement-curves of selected jet grouted tie-back piles

The examined displacements at the load tests as well as the sedimentation processes described priory (Krentz, 2015 and Kayser et al., 2007) lead to the conclusion that the jet grouted piles activates its resistance by the shaft friction resp. interlocking and not via the top of the column. This was confirmed by finite-element-simulations for the chamber walls. For activating the earth pressure at the top of the column, much larger displacements than determined would be needed.

6 Sustainability in the production of jet grouted tie-back piles

The cement consumption of the currently manufactured jet grouted tie-back piles is about 2.9 tons per running meter. For a 7.5 m long pile this means about 21.7 tons of cement. Considering that more than 1000 jet grouted piles will have to be produced, considerations have been made to reduce the consumption. By varying the manufacturing parameters, i.e. nozzle pressures, rotation and pulling speeds (in the different manufacturing phases) and the w/c-value, the theoretically required cement consumption could be reduced by up to 40% in the first tests, although further verification is still pending.

7 Conclusions

By extensive tests and examinations jet grouted tie-back pile could be recommended for the 5th lock chamber in Brunsbuettel. It could be demonstrated that even low w/c-value of 0,5 can be applied by the jetting method. By preliminary tests, the jetting parameters lead to a sufficient geometry of the jet grouted column with a diameter of 1.0 m and sufficient material properties, in respect to the concrete aggressive ground water.

As works continued, the jetting parameters had to be adapted on site by the current company to achieve the same results as at the preliminary tests. The parameters differ significantly. Hence, the equipment used by the company governs the resulting jet grouted column.

In the end, it was possible to prove, that with the manufacturing parameters established and the construction machinery used, the required properties of the highly load-bearing and resistant jet grouted tie-back can be achieved.

Quality management in the course of the ongoing project, such as quality load tests, load tests at additional construction piles and additional single jet grouted columns, assists in ensuring a permanent load bearing tie-back system with jet grouted piles for the next 100 years.

Further load tests are planned to investigate the time dependent behavior of the jet grouted tie-back piles in the concrete aggressive soil over the years. Therefore, provisions have been made for additional measurements by fibre optics at the threadbar.

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Authors

Martin Pohl
Federal Waterways Engineering and Research Institute, Karlsruhe
Kußmaulstraße 17, 76187 Karlsruhe
E-Mail: Martin.Pohl@baw.de

Joachim Abratis
Federal Waterways and Shipping Administration
Nord-Ostsee-Kanal, Alte Zentrale 4, 25541 Brunsbüttel

Gabriele Peschken
Federal Ministry of Transport and Digital Infrastructure
Invalidenstraße 44, 10115 Berlin