Design and validation of jetgrouting for the Central Station Amsterdam

French title

J.C.W.M. de Wit , P.J. Bogaards
Adviesbureau Noord/Zuidlijn Amsterdam, Royal Haskoning, Rotterdam
O.S. Langhorst, B.J Schat
VOF Stationseiland Amsterdam, Movares Nederland B.V and Arcadis Infra B.V.
R.D. Essler , J. Maertens
Consultants
B.K.J. Obladen, C.F. Bosma
Principal Contractor, CSO, Combinatie Strukton Betonbouw van Oord ACZ
J.J. Sleuwaegen, H. Dekker
Jet grouting Subcontractor, Smet Keller

ABSTRACT

The construction of the new North-South metro scheme in Amsterdam requires that the existing main railway station in Amsterdam is crossed by and connected to the new tunnels. This paper describes the design and validation of the jetgrouting that was carried out as part of the construction of a composite steel pile and jetgrout wall (the 'Sandwich Wall ') , the design of which has been reported in another paper.

RÉSUMÉ

Texte du résumé

1 INTRODUCTION

This paper is the second part of two papers which describe both the design and the execution of the jetgrouting required for the Central Station project. The first paper (De Wit *el al* 2007) deals with the design and construction philosophy of the work following the observational method whereas this paper will describe the design and validation of the jetgrouting.

The requirements for the jetgrouting are described in the paper by De Wit *et al* but may be summarised as follows:

1. To achieve the design diameter within limits of +- 20% of the diameter
2. To achieve a positional tolerance within 1% of the design location at any point of each column
3. To achieve a minimum strength of 1.75MPa (May 2005)

If the above requirements are achieved then the risk of any leakage of water or soil through are minimised and structural capacity is acceptable. In order to establish whether the above requirements could be achieved a number of trials were carried out in advance of the main jetgrouting to ensure that risk of gaps in the wall or inadequate strength were avoided.

Following completion of the trials, the main production jetgrouting commenced in May 2005 with ongoing quality control and validation using a number of techniques that are described below.

2 JEGROUT DESIGN LAYOUT

The design of the Sandwich wall consists of two rows of steel Tubex piles of diameter around 450mm surrounded by jetgrout material. The column layout consists generically of 800-1000mm diameter single system columns formed between the Tubex piles and 2000-2200mm diameter double system columns to infill the gaps between the two rows of piles and jetgrout perimeter columns. The jetgrout columns were jetted full height from a depth of around 29m (-28m NAP) to within 1m of ground level. Figure 1 shows the schematic arrangement of the wall in plan. The two lines of Tubex piles are around 2.5m apart and spaced at around 1m centres.

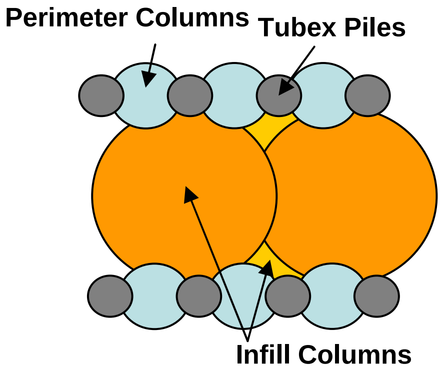

Figure 1 : Schematic layout of wall

Difficulties associated with the achievement of the design were the achievement of the positional tolerances and also the design diameters. In addition to these problems, a number of relic wooden piles remained within the footprint of the Sandwich wall which would also complicate and potentially compromise quality. Because of the historical importance of the Central Station building and the construction programme, it was absolutely vital that the Sandwich wall functioned correctly without causing unacceptable movements or distortion to the building. It was therefore considered paramount that the quality of the wall could be validated during the works to provide sufficient confidence for the following excavation. Because of this, a Steering Group of jetgrout experts was convened by the client to supervise the technical requirements and ensure that the best possible jetgrout solution was obtained. Because of this management structure it was possible to examine every facet of the jetgrout process and reach a consensus as to how it could be carried out most efficiently and to the highest standard. As a measure of how much detail was considered, the steering group met almost every week, twice a week for around 8 months before actual construction started on site and during construction.

3 TRIAL WORKS

The first trial was executed between February and April 2004 and consisted of a total of 6 single and 5 double system columns to investigate the two generic types of column (perimeter and infill) that were to be used on the project. The columns were jetted to a level of -28m NAP, approximately 29m below ground level. The columns were constructed within a sheet pile cofferdam and excavated to a depth of around 8m on completion. In addition to excavation of the upper parts of the columns, measurements were made of column diameter using both a downhole in column calliper and also by installing hydrophones at the periphery of the columns. Additionally measurements of spoil return density were carried out at frequent intervals as changes in spoil density can be related to diameter if some basic assumptions are made.

The results of the trial suggested that there was some scatter in diameter and that the required strength might be difficult to achieve. The main philosophy of this trial was to carry out the jetgrouting with both a precut or prewashing phase followed by a further jetgrout phase. The initial precut phase was to theoretically enlarge the hole to around a diameter of 40cm and thus allow for improved spoil return and less material to be cut with the follow on jetgrout phase. The measurements of diameter by both column callipers and the hydrophones gave some confidence that the required diameter had been achieved but strength was on the low side.

Following this trial the design of the sandwich wall was reevaluated and a lower design strength resulted. This assisted the jetgrout process but ultimately it was decided by the steering group that the most satisfactory solution could be obtained by carrying out a precut with significantly higher energy to actually construct the column diameter with this phase. The jetgrout phase was then used to create a high cement content by the injection of a low water cement ratio grout. This methodology has the benefit that lower pump power is required for the precut phase to achieve the high pressures and flows required and that the heavy jetgrout grout injected was more liable to displace the lighter precut spoil and give an enhanced strength through displacement rather than mixing.

Following this change in methodology it was concluded that a further small scale trial was required to validate the new approach and in May 2005, 5 further columns were constructed using the higher energy precut with grouts of differing density. The column calliper, spoil density and hydrophones were used again to validate diameters achieved. The results of this trial indicated that the high energy precut was successful but that a lower water cement ratio grout was needed to ensure that the clay material was lifted out of the columns.

Based on the results of this trial, the final parameters were set for the production jet grouting and work commenced within the Central Station building.

4 COLUMN PRODUCTION

The steering group considered that the production of each column needed very careful quality control and validation to ensure that the integrity of the Sandwich wall would not be compromised. It was therefore agreed that the following general sequence would be adopted.

4.1 *Drilling*

The drilling of each column was regulated to a maximum rate of penetration as it had been demonstrated during the previous trials that increasing rate of penetration gave more deviation. Following completion of drilling, the hole was surveyed by introducing an inclinometer probe down the central annulus of the jetgrout rods. This survey was repeated a number of times with a different probe orientation to give the maximum confidence on hole position.

Using this survey data, the as built drill hole position was plotted on a digital layout drawing and an assessment made as to whether the column could be:

- Jetted as normal
- The parameters adjusted to make a slightly larger column
- Only a partial depth jetted and the outstanding section rejetted at a later date
- Abandoned, grouted up and redrilled at a later date.

This initial quality control ensured that columns were only jetted when the column was positioned within its design tolerance and simplified later column production.

4.2 *Column Sequence*

Because of the length (around 28m) of each column and the necessity to precut and then jetgrout, it was considered that the column had to be precut in three sections. This was to ensure that the time between the start of precut and the start of jetgrout was kept to a sensible limit which would allow the jetgrouting to be carried out without the risk of excessive sedimentation or initial grout set. Measurements of diameter were also carried out following precut and this sequence assisted with maintaining free access to the bottom of the column for the calliper device. Because there were a number of differing parameters in use, control of sequence was very important and within some sequences, parameters would be changed depending on soil type or density.

Figure 2 shows a typical schematic sequence for a column.

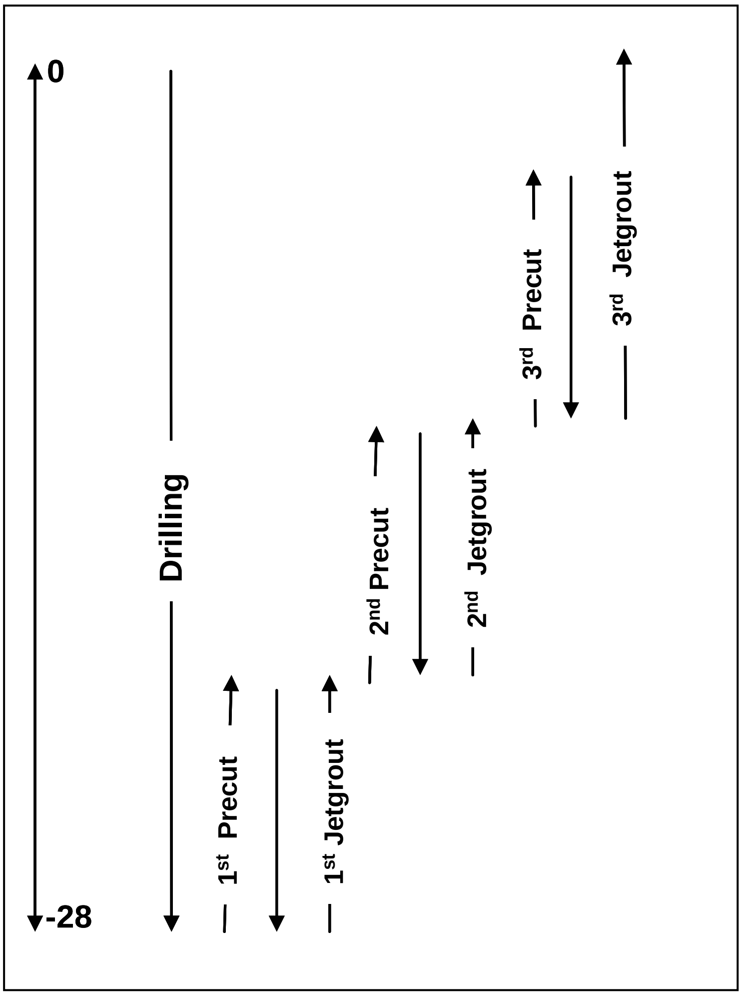

Figure 2 : Precut and Jetgrout sequence

4.3 *Column Jetting Parameters*

The jetgrout parameters for each type and diameter of column were established from the previous trial works and also updated as the works proceeded. The use of hydrophones and the column callipers allowed a high degree of confidence of the diameter achieved and the reliability of the jetting parameters in use. With the hydrophones it was also possible to adjust the parameters in real time if the feedback from the testing during jetting was unfavourable. (this is discussed in more detail below) Figure 3 gives an example of the parameters used for a 1000mm single system column.

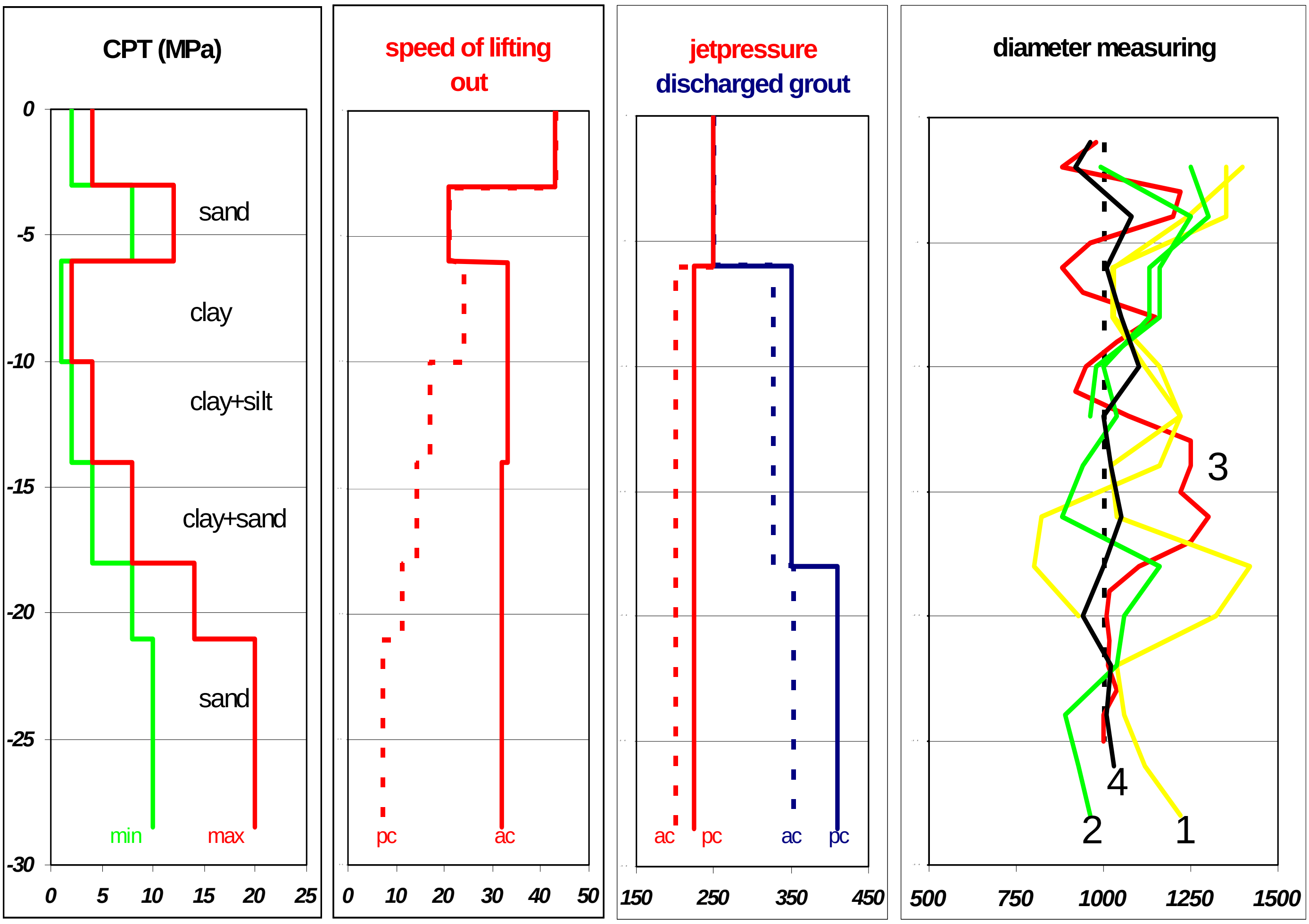

Figure 3 : Typical jetgrouting parameters 1000mm column

5 COLUMN DIAMETER MEASUREMENT

One of the most difficult aspects of jetgrouting in the past has been the verification of column diameter as this has often lead to design problems when insufficient diameter has been formed. Three methods have been developed on the Central Station project which is discussed below.

5.1 *Column Calliper System*

The contractor provided a hydraulically activated column calliper for use on the project. A schematic illustration of the device is given as Figure 4. Considerable work was required, prior to the start of, and during construction to enable a more accurate interpretation of the results.

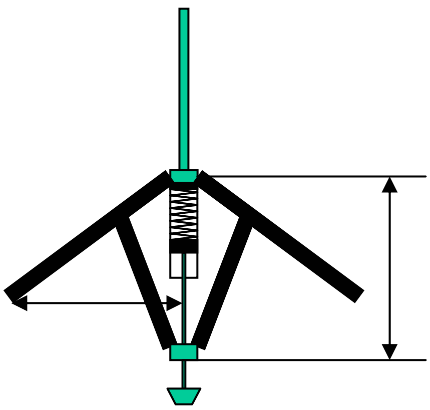

Figure 4 : Schematic section of column calliper

Figure 5 shows a typical result of a diameter measurement. The calliper operates by applying a pressure to a hydraulic cylinder which expands the arms as shown on figure 4. The displaced volume and pressure of the cylinder are measured at the surface. Before an actual measurement is carried out, a calibration of the device is required. This is carried out by extending the arms and measuring the resulting pressure and volume change within the system. On Figure 5, curve A is the calibration of diameter against displaced volume and curve B is the calibration of applied pressure against displaced volume. To interpret the actual column measurement the applied pressure is plotted against displaced cylinder volume (curve C). Because the behaviour is slightly different in the ground the device does not follow the calibration line and the final portion of curve C is projected back to curve B. The intersection with curve B then defines the volume at which point the arms touch the sides of the column and then the diameter can be estimated from curve A as shown. A further correction (not shown) is required for the expansion of the hydraulic hoses under pressure but surface calibrations with the arms placed between concrete and clay blocks proved that the measurements are repeatable and accurate. In a final development, digital inclinometers were added to the arms which gave a better clarity in the measurements.

It is considered that this device gives good indication of actual column diameter and is an important advance for the jetgrouting industry.

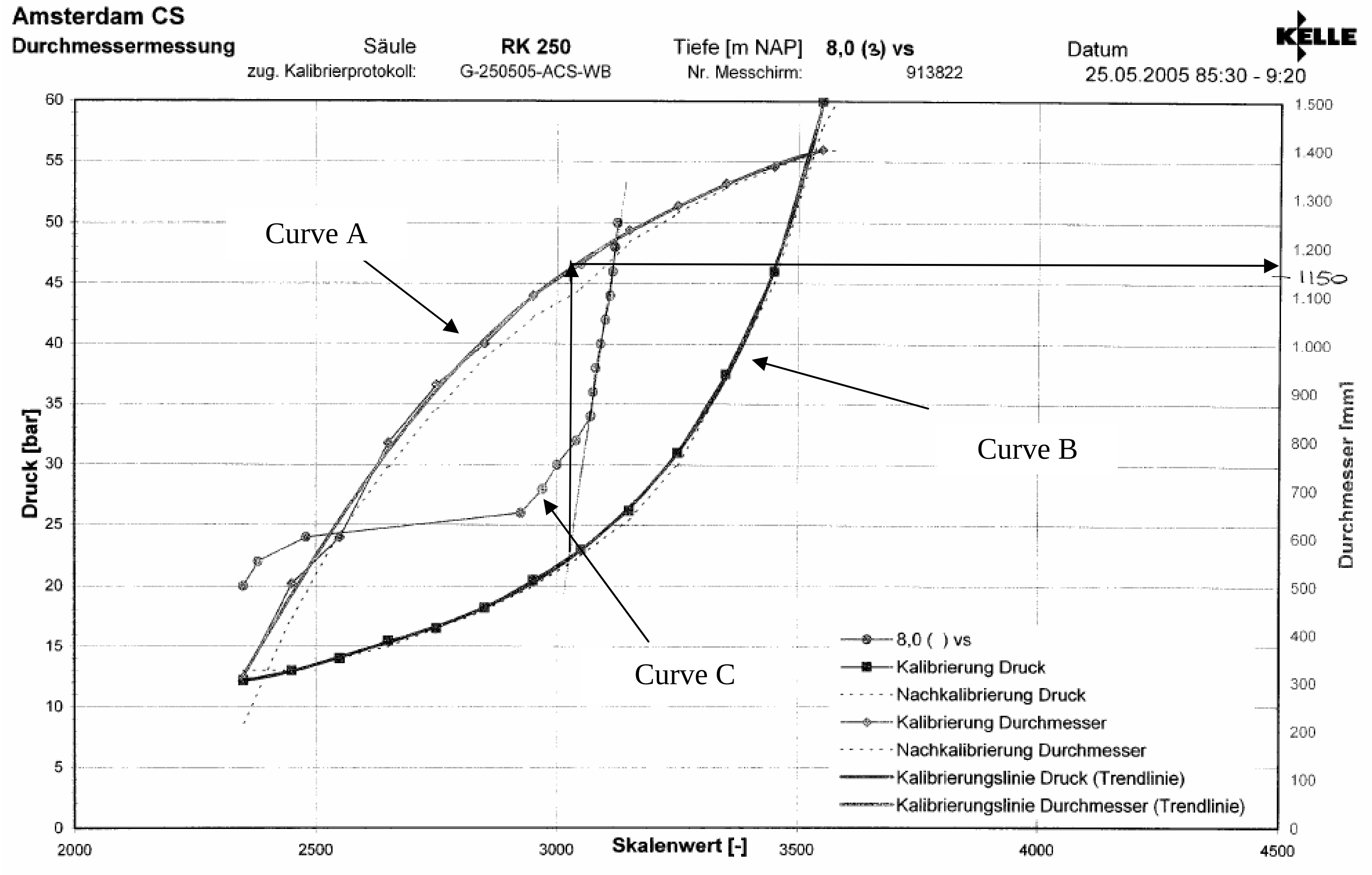

Figure 5 : Diameter measurement plot

5.2 *Hydrophone System*

In addition to the use of the column calliper, a hydrophone system was also deployed. Figure 6 shows the schematic diagram of the operation of hydrophones.

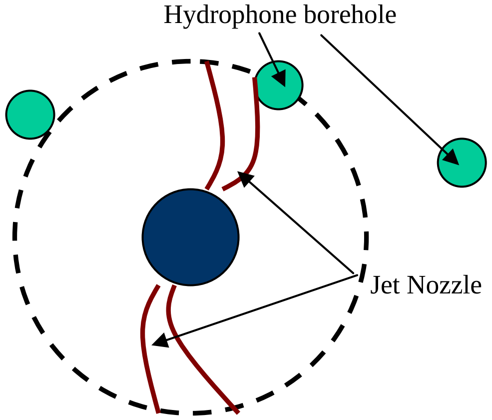

Figure 6 : Principle of hydrophone measurement

In operation a number of small diameter holes are drilled around the periphery of the column to be tested. These can be 50-75mm in diameter. During the jetgrouting process, microphones placed at a depth close to the level of the jetgrout nozzle(s) are used to measure the noise resulting from the impact of the jet on the hydrophone tubes. Placing the tubes at differing distances from the centre of the column allows an estimate of the diameter range depending on the response of the system. Furthermore, the hollow Tubex piles were also used to carry out hydrophone measurements during the jetgrouting works. Here, the main purpose was to verify that closure between the perimeter column and steel pile was achieved. Figure 7 shows a photograph of a measurement setup and Figure 8 the resulting display used during jetgrouting. The amplitude of the waves matches the passage of the jet and thus the diameter can be proved. It is also possible to adjust the jetgrouting parameters if the results of the hydrophones are not conclusive thus for example the lift speed can be reduced or increased and the response on the hydrophones noted. It is therefore possible to match the jetgrouting parameters to the required diameters more efficiently.

Figure 7 : Hydrophone test setup

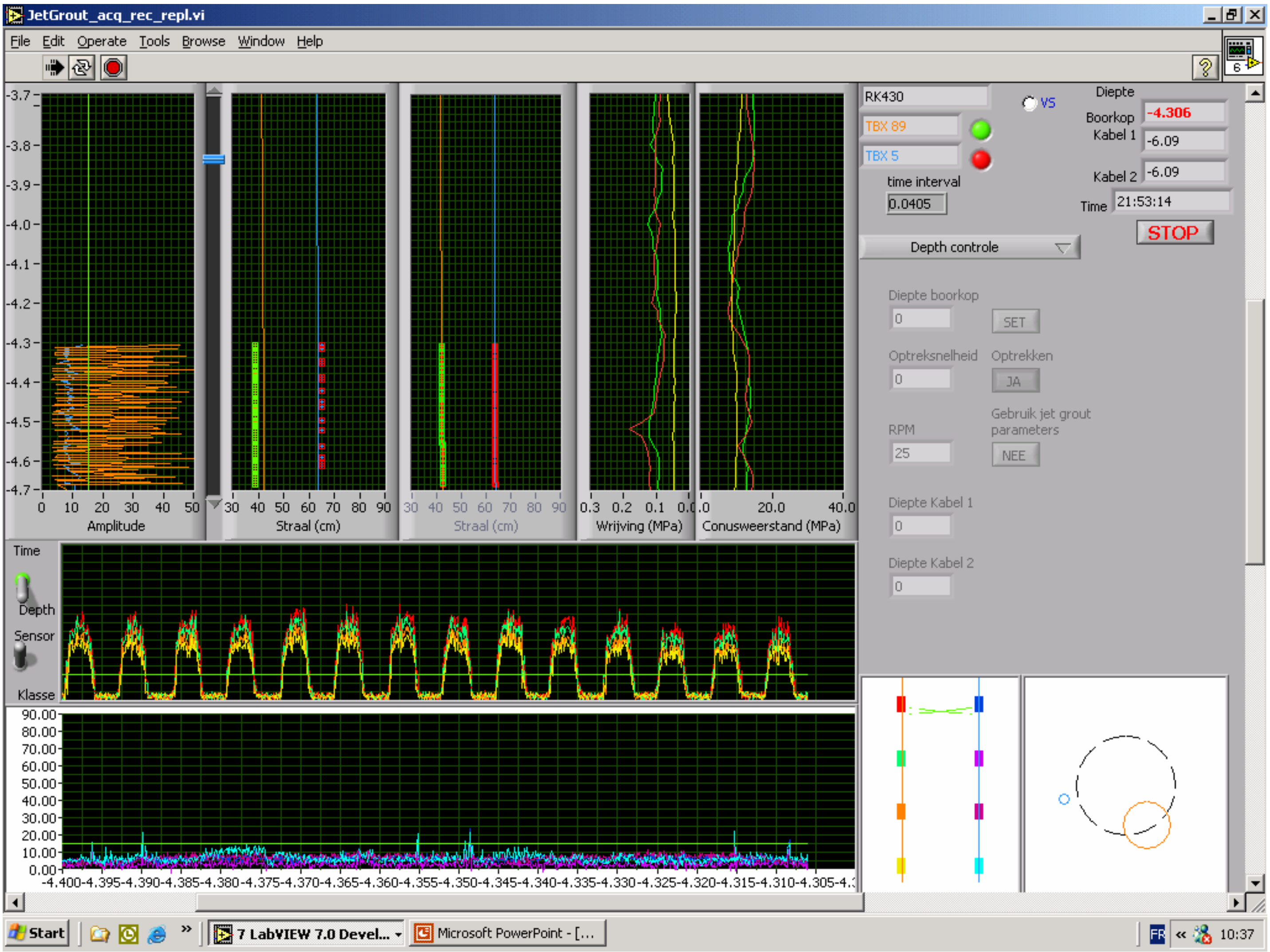

Figure 8 : Hydrophone measurement display

5.3 *Spoil density measurements*

In addition to the use of the column calliper and the hydrophones, the density of the spoil returns from the borehole was measured at 1m intervals during precut and jetgrouting. In principle this is a very low cost option for diameter measurement as it does not delay the operation and is simple to carry out. At Central Station a number of methods were investigated including hydrometers and mud balances. The interpretation of these was found to be difficult if the highest accuracy was required and finally a sample was measured by filling a 1 litre container and using a digital balance to weigh it. At a later stage a 1 litre container with a close fitting lid was manufactured to give more repeatability of volume.

The theory of relating spoil return density to column diameter has been reported in a number of papers (Kauschinger *et all* 1992), (Croce & Flora 2000). Essentially a mass balance approach is adopted to the material within the jetgrout body and the excess material ejected from the borehole. Assumptions are made that either the column composition is identical to the spoil ejected or that certain percentages of the original material are retained within the column. Usually for sands the first relationship is used but as larger particles or clay are present then the mass balance approach becomes more complex. Figure 9 shows the results of a measurement by both spoil density and column callipers for a column. Because of the overlap of the column with previously constructed columns, the calculation of spoil density is more complicated as an assessment of the actual column volume being cut is required. For the perimeter columns the areal percentage cut was around 80-85% whereas for the infill columns this ranged from 40-55%. This change in column volume has a profound effect on calculation of spoil density or conversely back calculation of diameter and if a truly accurate solution is required then an iteration between adjustment of areal percentage and predicted diameter is required. However the results can give an indication of column diameter to within 20%.

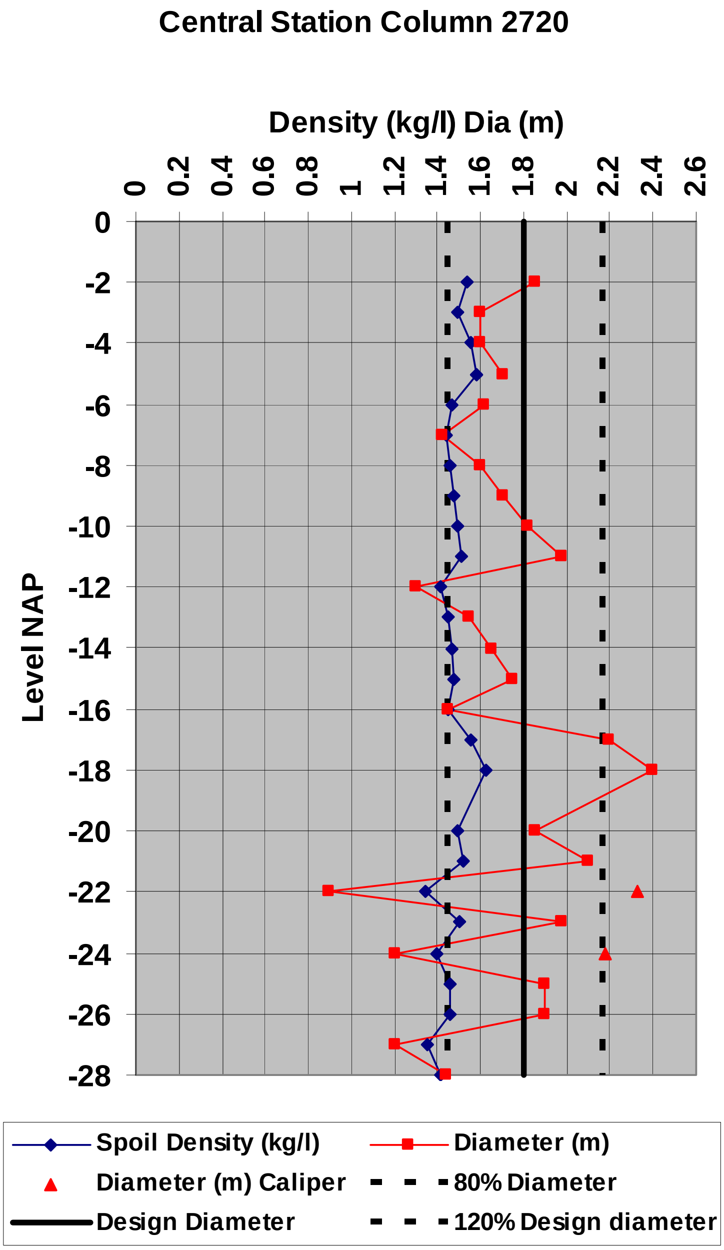

Figure 9 : Results of diameter measurement

6 CONCLUSIONS

Significant advances have been made in Amsterdam in improving the quality control of the jetgrout process. The use of column callipers, hydrophones and spoil density measurements all give confidence to the actual diameter of jetgrout column produced and it is expected that with further development in all three techniques a better accuracy can be obtained.

The use of a two stage process of a precut and jetgrout phase allows the separation of column diameter creation and column strength. It is considered that this approach will allow the use of higher design strengths in clays than was previously considered.

7 REFERENCES

De Wit , Bogaards, Langhorst, Schat, Essler, Maartens, Obladen, Bosma, Sleuwagen, Dekker 2007. Design and construction of a metro station in Amsterdam

Kauschinger , Hankour, Perry 1992, Methods to estimate Composition of Jet Grout Bodies. Proc ASCE Conference Grouting, Soil Improvement and Geosynthetics, New Orleans : 194-205