# Design and construction of a metro station in Amsterdam. Challenging the limits of jet grouting

## Projet et réalisation d'une gare de la Métro d'Amsterdam: le défi du 'jet grouting'

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ABSTRACT

Beneath the Amsterdam Central station is an excavation created of the North/South Line, within a tunnel is immersed. This is characterised by the application of a particular technology in the form of, *inter alia*, the so-called 'sandwich wall'. This is a composite wall consisting of two rows of steel piles with a body of jetgrout columns in-between. This wall acts both as an excavation support wall and also provides vertical bearing. The installation of the wall, within these specific conditions (limited height, sensitive historical building, train station in service), within the design requirements set in terms of construction tolerance and water and soil retention, may be regarded as being a pioneering achievement. Especially for the jet grouting an integrated design and construction approach, including an extensive monitoring programme was needed. Work commenced on the sandwich wall in 2003, when the wooden piles were extracted at the locations where the sandwich wall was to be constructed; in 2004, the steel piles for the southern wall sections were installed. From May 2005 to February 2006 for the southern part of both walls jet grouting was carried out.

RÉSUMÉ

Pour la construction de la ligne de métro Nord – Sud des fouilles doivent être réalisées en dessous de la Gare Centrale pour la mise en place dïun tunnel immergé. Cette réalisation est caractérisée par l'utilisation de techniques particulières comme par exemple des ⟨⟨parois sandwich⟩⟩. La paroi sandwich est une paroi composite composée de deux rangées de pieux métalliques et de colonnes de ⟨⟨jet⟩⟩. Cette paroi est un élément de soutènement et de fondation. La réalisation de cette paroi dans des conditions très difficiles comme: des hauteurs réduites, travaux à réaliser sous un bâtiment historique sensible, dans une gare en service et des exigences très sévères vis à vis des tolérances du chantier de la construction et de la pénétrabilité de l'eau et du sol peut être considéré comme un travail de Pionnier. Pour la réalisation du ⟨⟨jet grouting⟩⟩ un projet intégré ainsi qu'une méthode d éxécution appropriée et un programme de suivi détaillé ont été spéciallement nécéssaires. Ces travaux ont commencés en 2003 par l'extraction de pieux en bois situés à l'endroit de la future paroi. En 2004 pour la réalisation de la paroi des pieux métalliques ont été instaleés dans la partie méridionnale, et entre mai 2005 et février 2006 les travaux de ⟨⟨jet grouting⟩⟩.

## 1 INTRODUCTION

The new 'Noord/Zuidlijn' underground link connects the northern and southern suburbs with the city centre. The most complicated underground station is to be constructed beneath the Amsterdam Central (Tram) Station (Photo 1).

The train station was built around 1880 on an island dredged beforehand in the IJ waterway. The building is supported on some 9,000 wooden piles. It is a fundamental requirement that during the construction of the underground link, the trains should continue to run and the inconvenience to passengers should be kept to a minimum.

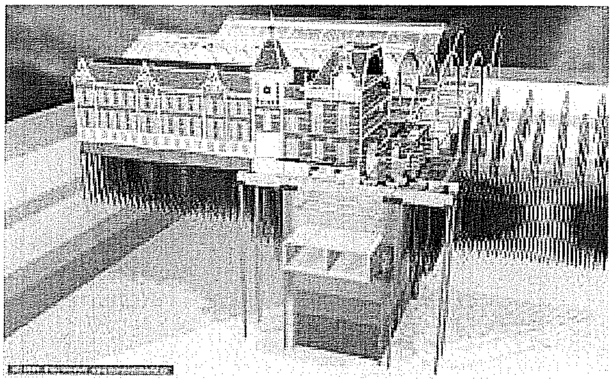

Figure 1. Impression of the Amsterdam central station.

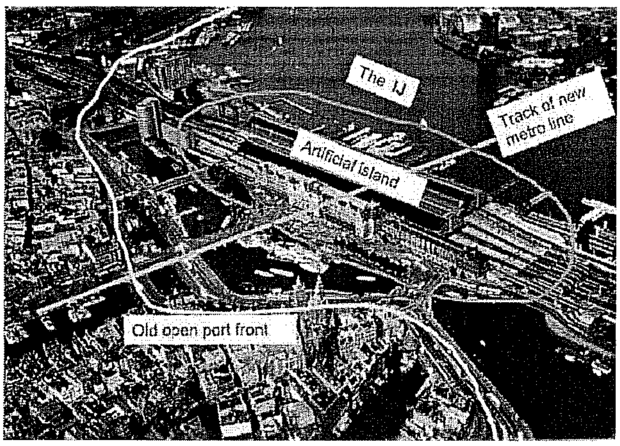


Photo 1. Location of the underground line.

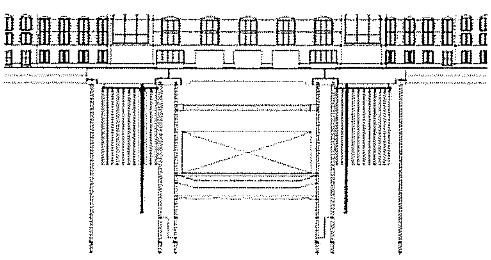

Figure 2. Construction phases.

The renovation is being carried out over a relatively small footprint within the largest public transport junction in the Netherlands and the project is accordingly highly complex. The metro station will be constructed beneath the station building in various construction phases, as illustrated in Figure 2.

## 2 CONSTRUCTION PHASES

To get a better understanding of the works, the construction phases are described below:

1. Extract existing wooden piles;
2. Install steel Tubex piles;
3. Install jet grouting body;
4. Carry out station building support works;
5. Lower ground water level;
6. Excavate in the dry

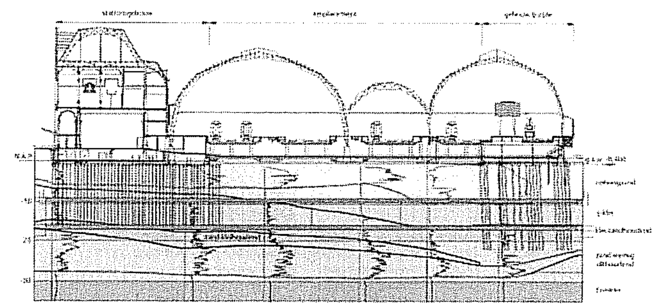

Figure 3. Longitudinal section of the station.

7. Install low level grouted strut;
8. Install high level steel strut frame;
9. Raise water level;
10. Excavate in the wet;
11. Float in and immerse tunnel;
12. Backfill with soil.

## 3 OVERALL SOIL DESCRIPTION

The soil conditions from ground level (+3 m NAP [Amsterdam Ordnance Date]) consist of an approx. 8 m thick layer of dredged sand (down to NAP −5 m) overlying the relatively weak 'IJ clay' containing sand bands to approx. −15 m NAP. Below this layer down to approx. −28 m NAP, is a medium dense, locally dense, 2nd sand layer, consisting of slightly silty sand and clayey sand. Beneath the level from approx. −28 m NAP, there is an approx. 30 m thick clay layer (Marine 'Eem clay' and Glacial clay). The third sand layer, which has a high cone resistance, is found from −56 m NAP; this layer has high bearing capacity. The highest ground water level measured is −0.25 m NAP within the dredged sands, approx. −1.50 m NAP in the second sand layer and in the third sand layer −3.00 m NAP. The geotechnical profile is shown in the following Figure 3.

## 4 THE DESIGN OF THE SANDWICH WALL

The sandwich wall that was developed for this part of the project was adapted to the specific conditions under the A'dam CS. The protection of the station building, as a national monument, was, in particular, the main priority during the design development. The design of the sandwich wall is based on a robust, stiff wall, which is constructed from smaller components. As a result, the equipment required is relatively light and can be used within the station building without excessive modification to the building structure.

## 5 GEOMETRICAL ASPECTS

The sandwich wall consists of two rows of steel Tubex piles (diameter 457 mm, thickness 25/16 mm) with a length of 26 m to 60 m. The piles in one row are approx. 1 m centre to centre and the pile rows are approx. 2.5 m apart. The piles are provided with rings (32 mm) in order to ensure full mobilisation of shear strength within the grout body. The piles are installed in short sections (2–5 m) using a drilling rig with an extension (Topdrill) specifically designed for this purpose (Photo 2).

The old wooden piles in the area of the sandwhich wall, were extracted using a special for this job developed method. With this method extracting the pile and filling the hole with sand was carried out at the same time, resulting in an minimum of impact on the environment. The space between the piles is filled by jetgrout columns having a diameter from 800–1200 mm and a length of 28.5 m. The space between the pile rows is filled with two rows of jetgrout columns with diameters varying from 1400–2200 mm and lengths from 28.5 m.

## 6 STRUCTURAL ASPECTS

The retained height of the wall is approx. 18 m, the water level difference across the wall being 3 to 5 m. The horizontal stability of the wall is provided by the structural interaction between the steel Tubex piles and the grout body, supplemented with temporary struts at three levels. This results in an extremely stiff wall, with predicted deformations being of the order of 20 to 30 mm.

The sandwich wall also transfers the vertical loads resulting from supporting the foundations of the building at the location of the construction pit, via a number of Steel piles in the Sandwich wall that extend to the 3rd sand layer (length 60 m). The selected wall system is based on the assumed interaction between the piles and the jetgrout. However, it has the disadvantage of having a relatively brittle failure behaviour.

The safety factors used have therefore been increased considerably, with as an in-built safety factor, the fact that resistance to failure is guaranteed by the strength of the two rows of Steel piles (the horizontal deflection does however increase).

## 7 SEEPAGE AND SOIL RETENTION OF THE WALL SYSTEM

Other important design are as the resistance to seepage, soil retention. Practical experience has shown that the water-tightness of a jet grout body consisting of columns is particularly sensitive to variations in construction tolerances.

The co-ordination of the design preconditions and the construction is very important in this regard.

## 8 RISK ANALYSIS AND DESIGN REQUIREMENTS

Extensive risk analyses were carried out for this particular wall during the design phase. A failure of the wall system may indirectly cause damage to the station building of A'dam C S. It is therefore very important to limit and control the risks as far as possible. As part of a major study in preparation for the Noord/Zuidlijn, jetgrouting was examined in detail through a jet grouting trial carried out in the north of Amsterdam. A number of columns were produced for the design of the sandwich wall; the achievable final strengths and the minimum diameters to be produced in the Amsterdam soils were, in particular, investigated.This trial provided sufficient confirmation for viability of the design. As a result, the design requirements were established, that however can be described as ambitious. The design assumed a vertical deviation, measured over the full length of the Tubex pile, of at most 0.5% of the depth from ground level. For jet grouting, the vertical deviation had to be less than 1%. The variation of the actual diameter relative to the theoretical diameter has to be less than 10–15% depending on the actual diameter. The characteristic (design) value of the compressive strength was determined as 1.75 N/mm$^2$ at 28 days.

## 9 FUNCTIONAL ANALYSES BASED ON MONTE CARLO SIMULATIONS

A special for this job developed program (by GeoDelft), based on Monte Carlo simulations was developed to improve the jet grout column layout. The program even enabled the engineers to adjust the layout during construction, based on as built information. The geometry of the jet grout columns after construction stipulates whether the grout will interlock with the steel piles and the adjoining columns. Voids can arise in the grout body by rake, deviation of drilling, deviation of the diameter, shadowing and misdrilling (into tubex or pre installed column). All columns are subject to these deviations and adjoining columns are interdependent. An elaborate study of the optimal grout pattern with regard to these deviations has been made in order to arrive at a jet grout body that is as homogenous as feasible. Within this model it is possible to simulate the jet grouting process.The model of this simulation is based on square elements. The elements near the boundaries of the jet grout columns are condensed by a ratio of 3 in order to reduce computing time and to allow the best fit for round shapes. The location, diameter and inclination are presumed in the model in a stochastic distribution. For each element of the grout pattern a random draw of the construction deviations is made of which subsequently a computation is made whether or not there will be grout in an element.

The model takes into account shadowing and misdrilling. In order to obtain enough relevant results over 10000 draws are considered. The amount of grout present in the mass is computed for each draw along with an evaluation on the presence of a pass through the jet grout mass. In case of a pass through the mass

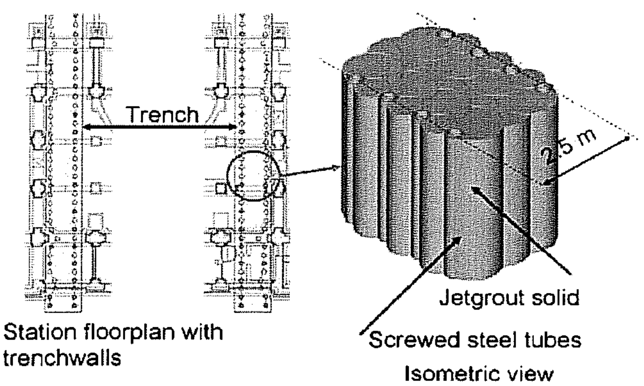


Figure 4. Specific topic of the trench.

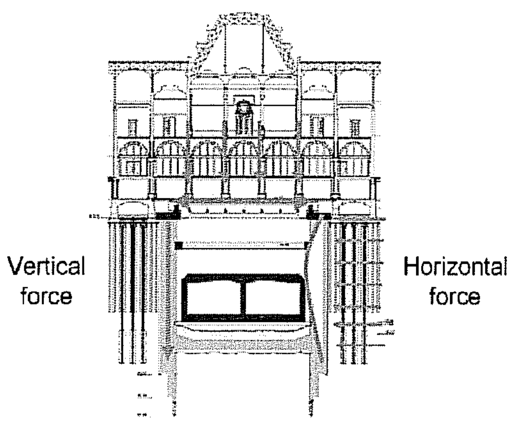


Figure 5. Forces on the wall.

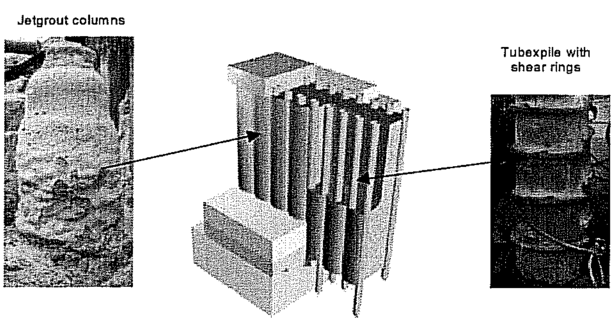


Figure 6. Elements of the sandwich wall.

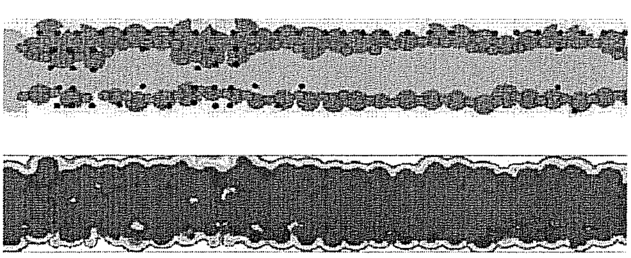

Figure 7. Monte Carlo analyse.

the sandwich wall will suffer leakage. The summation of the number and leakages per model determines the chance on leakage for the jetgrout pattern. Furthermore based on these computations a drawing can be made of the chance of grout per model. A visualization of the results is shown in Figure 7. By computation of various grout patterns with this model it is possible to obtain insight on the best method by which the jet grout body should be made. Finally a basic pattern has been developed which consequentially was optimised on various locations by trial and error.

## 10 FROM THE JET GROUT TRIAL TO THE FINAL WORK

Once the work was awarded, a second jet grouting trial was carried out on site. The objective of the second trial was to enable the subcontractor to adjust the process on site before starting on the sandwich wall, to confirm his expertise in the field of jet grouting and to understand the risks more thoroughly. During the trial, measurements of the diameter, variations in diameter using both borehole callipers and hydrophones, the verticality and strength of the jet grout columns were carried out. During this trial the focus was on achieving the diameter, variation in diameter, verticality and strength in the specific site conditions.

The results showed an even higher than expected sensitivity to the varying local ground conditions. After careful evaluation adjustments were made the process and a justified relief to some of the design requirements appeared possible:

- Separation of the 'diameter' and 'strength' construction phases. The pre-cutting phase created the full diameter, and the post-jetting phase then provided sufficient binding agents for the strength.
- Formation of columns in sections (from 5 to 10 m in length) in order to limit the time effects.
- Adapting strength requirements to the actual project situation. The characteristic value of the compressive strength of the jetgrout at 120 days was to be 1.5 N/mm$^2$.
- Providing more latitude in the design, allowing greater deviation in diameter. The design was adapted to allow a variation of $\pm 20\%$.
- Setting up an extensive measurement programme for the jetgrouting process (process instrumentation, diameter measurements using borehole callipers and hydrophone measurements, strength measurements).
- Set up a 3D model, taking into account 'as-built' information (3-D measuring of steel piles, remaining wooden pile (parts), successive production of jet grout columns). This required a highly focussed approach and supervision (observational method), in which the design and/or construction parameters can be adjusted, if necessary.

## 11 MANAGEMENT OF FINAL WORKS OPERATIONS

### 11.1 *General*

When adopting the observational method, information was obtained from work completed and used to adjust work still to be carried out. Prior to starting

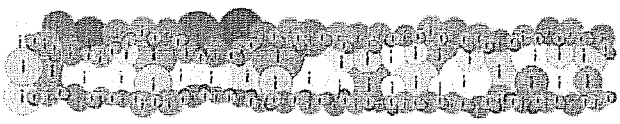

Figure 8. plan view indicating Tubex piles and grout perimeter/infill columns.

the jet grouting process, this meant that the basis of the jet grout model was adapted to the actual position (and deviation) of the steel piles that had already been installed and but also to the wooden piles (or parts) that could not be extracted.

When carrying out the jet grouting of the sandwich wall, the focus was on both the individual products (the separate columns) and the final product (the wall system). For both processes, measurements were carried out and options for verification and adaptation provided. Maximum possible control on site was thus obtained in each phase and in each component. Figure 8 shows a plan view indicating the steel piles in red, the jet grout perimeter columns in blue, and the jet grout infill columns in yellow/brown.

The basic premise of the methodology applied is that if a condition of a particular component of the wall satisfies the requirements set, the possibility of failure of the wall system (end product) is minimal. In order to meet this condition, it is important that all of the individual columns are produced with the utmost precision, whereby every column is treated individually. A work plan is accordingly drawn up for every column. This plan may be regarded as a script for the production and contains all of the relevant information for the implementation, such as design data, the jet grouting parameter plan, measuring regime, risk table and implementation protocols (method for dealing with deviations observed during implementation).

The best picture possible must be gained of the diameter and strength of the constructed columns by means of the recorded machine data (lift speeds, rotational speeds, pump pressures and outputs, etc.), measurements carried out (inclination measurements, diameter measurements using borehole caliper and hydrophones, spoil densities, etc.). The logbooks of the works also list important events and the records of additional changes sanctioned by the inspectors.

The result is processed in the 'as-built' layout to determine the actual quality, in order thus to be able to assess whether adaptations are required to the design and/or implementation and, if so, to provide proposals to do so (verification and adaptation).

### 11.2 *Implementation*

Determining the various jet grout parameters proved to be a difficult task for this project, in view of the complex preconditions. The following factors had to be taken into account:

- The significant depth of jetting.
- The highly heterogeneous and variable nature of the soil.
- The various specified diameters, including adjustment options during production.
- The provision of limited tolerances in the diameter (<20%) of the column in order to prevent a shadowing effect in the production of the neighbouring columns.
- The determination of the correct fluid density of the jetgrout slurry used during pre- and post-cutting in order to ensure smooth discharge of the return liquids and to prevent blockages.
- The use of as little air as possible in order to prevent local variations in ground water pressure (limitations effects on building).

The mono-jet system was used for the smaller diameters from 800–1200 mm, and the bi-jet system for the diameters from 1400–2200 mm. The columns were produced in two operations, namely pre- and post-cutting. In the case of pre-cutting, the entire diameter was cut using a low density grout slurry, whereas in the case of post-cutting, the column was homogenised using a higher density grout slurry, the required cement content of the column thus being achieved. Important was to produce the column in sections, so as little time as possible elapsed between the two phases, as the trials revealed that the end result was influenced favourably using this method. In order to accommodate the highly variable nature of the soil, individual layer divisions and associated parameter sets were established for each layer.

At some locations, up to seven sets of parameters had to be defined for one specific diameter. Everything was set out in advance by the engineers in working plans and protocols were also provided for the deviations that could be expected. Adapted parameters were provided in these protocols for these divergent situations. The agreed parameters were tested in two further trial phases and during the works and, if necessary, adjusted in response to the numerous measurements.

### 11.3 *Assessment of the columns*

Each column was intensively assessed immediately after implementation; this was necessary in order to be able to determine whether work could continue on the basis of the jet grout model or whether corrective measures were necessary. If a column met the design requirements, adjustments were not necessary and work could continue on the basis of the grout model. If the column did not meet the design requirements, corrective measures could be necessary. Corrective measures were taken from within the design or the works process (e.g. change off set column, diameter, additional column). The assessment related to the quality of the produced column. The analysis consisted of various components, namely:

- Monitoring the work process.
- Analysis of the column log, drawn up by the inspector. This indicates the particular details of the implementation process.

- Analysis of the measurement data; the density of the return slurry (indication amount of excavated soil/estimation of the diameter).
- Analysis and calibration of the applied jet grout parameters (kinetic energy analyses estimation diameter).
- Analysis of the borehole calliper measurements with which the diameter is measured.
- Analysis of the hydrophone measurements in Tubex piles and specially installed tubes (diameter indication).
- Monitoring the compressive strengths (based on return slurry and cores).

### 11.4 *Assessment of the wall*

The monitoring of the end product is oriented more to the functioning of the wall as a system. This means that the monitoring emphasis and associated measurements are oriented more at the seepage, soil-retention and strength of the wall. These aspects were tested as soon as possible in order to make any necessary adjustments within the working process.

In this case, also the information that became available during the production of the individual columns was used and in this way potential risk areas could be identified i early stage. Additional measurements could be considered if necessary. Leakage detection measurements were then carried out in order to trace any deficiencies in the wall.

In the EFT (electro-flux tracking) system, a controlled and defined electrical signal is introduced into the ground water on the outside of the sandwich wall and is detected on the other side of the structure by means of a sensor. If there are gaps in the wall, the electrical energy will be concentrated through them. An increased electrical potential relative to the watertight sections was measured on site.

The results of the measurements were reported for each soil layer by means of isolines Once the entire wall has been completed, pump tests will then be carried out within the excavation. If, at that stage, there are still substantial imperfections in the wall, it is is still possible to take back-up measures, for example local freezing, further limiting of the water level differences along the wall, etc.

## 12 MONITORING

The station building was monitored continuously during the operation phase, whereby three independent systems were used, namely:

- Geotechnical ground monitoring (inclinometers, extensometers, pore pressure transducers).
- Water level system for continuous measurement of the movements of the structures inside the building.
- External building monitoring, in which the façade of the station building was continuously measured by means of 'total stations' positioned outside the building.

The fact that these measuring systems operated independently of one another provided an optimum risk limitation situation, in which the systems monitor and validate one another. Furthermore, temporary malfunction of one system does not affect the continuation of the work, because the building can still be monitored.

## 13 CONCLUSIONS

An innovative approach for jetgrouting under difficult conditions was developed for the sandwich wall. Since there was a strong relationship between design and construction, the success of this method depended on good cooperation between the client's designers and the construction experts of the contractor. Implementing adjustments during construction required an intensified supervision coupled with a high flexibility from all involved and appeared to be the key to success.

Looking back at the first phase of construction, the results achieved seem to be very satisfactory, however the intensive methodology applied appears to be necessary to be continued to the conclusion of the works.