JET GROUT STRUT FOR DEEP STATION BOXES OF THE NORTH/SOUTH METRO LINE AMSTERDAM - DESIGN AND BACK ANALYSIS

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INTRODUCTION

The new North/South metro line in Amsterdam contains several stations, some of which with an excavation depth of 30 m below surface. The design of these station boxes is very much determined by the adjacent historic buildings, high water table and the relatively soft soil. A lot of effort is put into minimising the settlements of buildings with shallow pile foundations. For this purpose, the walls of the station boxes consist of 45 m deep stiff diaphragm-walls. Apart from steel struts, an extra measure was taken to prevent wall deformation: a jet grout strut. The uncertainties of material properties and construction tolerances demand extra attention in the design stage. In order to deal with these uncertainties, the observational method was adopted. This paper addresses the process of the design, monitoring and evaluation of the jet grout strut of the Ceintuurbaan station.

CEINTUURBAAN STATION - GEOMETRY AND BOUNDARY CONDITIONS

Geometry

The Ceintuurbaan station box is 210 m long, 11 m wide and 31 m deep. Diaphragm walls (D-walls) of 45 m depth enclose the building pit. These are supported at 6 levels by steel struts or concrete floors. The design comprises a 1,5 m thick jet grout strut, at 33 to 34,5 m depth.

Geotechnical conditions

The geology, depicted in Figure 1, is characteristic for the centre of Amsterdam. The stratigraphy is formed by a glacial basin filled with sediments. The 3rd sand layer, relevant as highly permeable aquifer, is at its base. The glacial Drenthe clay layers and the fluvioglacial intermediate sand are deposited in the Saalian period. These glacial deposits are overlain by marine clays of Eemian age. Above, the 1st and 2nd sand layer, often separated by the more silty Allerød layer, have been combined into one layer here. These two medium to dense, aeolian (1st) and fluvial (2nd) sand layers are of Weichselian origin. On top, the Holocene deposits have been condensed into one layer too. This unit consists of a tidal sand and mainly of soft clay and peat layers.
The sand layers are permeable, water bearing strata and have al a head of approximately -3 m. The freatic level in the Holocene layers is circa -1 m.

Description	γ_{sat} [kN/m^3]	φ' [°]	c' [kPa]	$E'_{50;ref}$ [kPa]	OCR [-]
Holocene layers, soft PEAT / CLAY / SAND	15	28	3	8000	n/a
1st & 2nd sand layer, (medium) dense SAND	19	34	0	34000	n/a
Eem layer, overconsol. marine firm CLAY	18	32	15	11000	2,0
Intermediate layer, medium SAND	19.5	33	0	25000	n/a
Drente layer, overcons. glacial firm CLAY	19.3	33	11	15000	1,5
3rd sand layer, dense SAND	19.5	35	0	35000	n/a

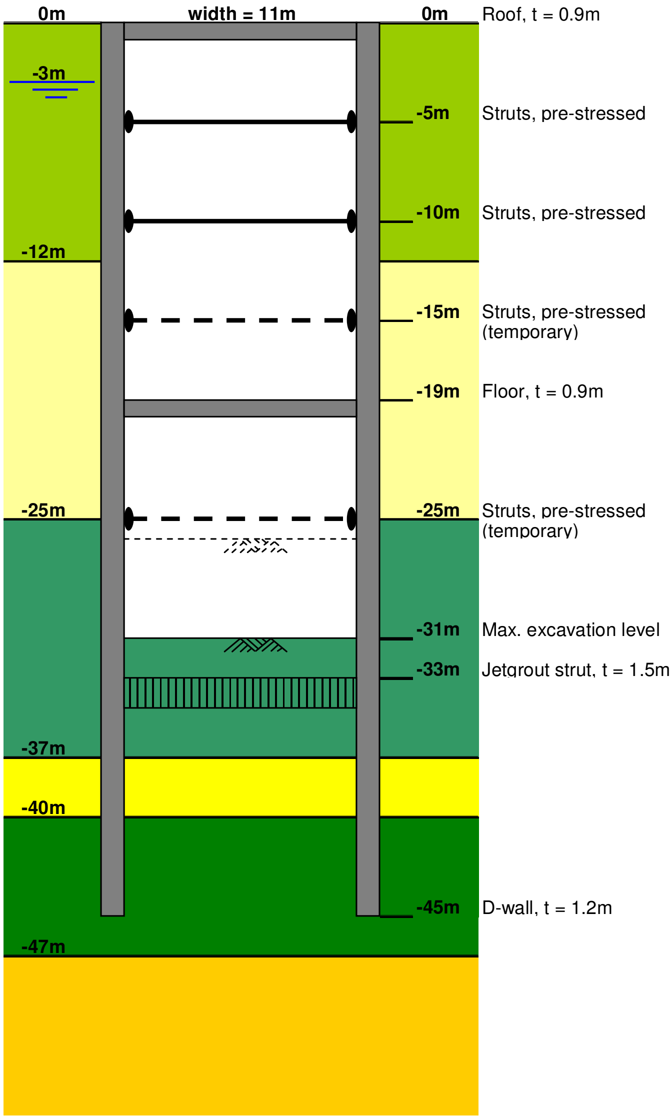

Figure 1 - Geometry and soil parameters

For this paper's case study, especially the Eem clay layer is of interest. A summary of geotechnical parameters for all layers is presented in Figure 1. For further reference, more data on the marine Eem clay are listed in table 1.

Table 1 - Geotechnical parameters Eem clay, mean values

Parameter			**Eem clay**
water content	w	[%]	36
liquid limit	w_L	[%]	42
plastic limit	w_P	[%]	23
liquidity index	I_P	[%]	19
undrained shear strength	c_u	[kPa]	150
compression index	C_c	[-]	0.358
secondary compression	C_α	[-]	0.0044
swelling index	C_{sw}	[-]	0.033
consolidation coefficient	c_v	[m^2/s]	$1*10^{-6}$
permeability	k	[m/s]	$2*10^{-9}$

Building settlements
Adjacent to the station box are over 50 buildings, most of which have 13 m long wooden pile foundations (pile toes in the upper part of the 1st sand layer). The distance from the buildings to the D-walls is 3-4 m. As the excavation reaches far beyond the foundation depth, the deformation of the D-walls has to be minimised.

Purpose
The main purpose of the jet grout strut is to limit the settlements of adjacent buildings to 25 mm. From FEM-calculations it followed that, to fulfil this requirement, the 1,5 m high jet grout strut should have an overall stiffness of at least 1000 MPa. At lower values, settlements of adjacent buildings would become too large. However, to prevent cracking of the D-walls due to bending moments, a maximum value of 2200 MPa was demanded.

GROUT STRUT DESIGN

Jet grout description
A jet grout body is constructed by injecting grout under high pressure into the soil through nozzles on a rotating drill string. The drill is moved upward slowly, thus creating a homogenous column of mixed grout and soil. By making several columns, either overlapping or not, the strength and stiffness of a soil layer is improved.

Design approach
The relatively small window of the grout strut stiffness (1000 MPa < E < 2200 MPa) leaves the designer with a difficult task, especially when taking into account the uncertainties that are faced during design and construction. The material properties of the grout body depend largely on the soil type and the cement content, which itself depends on process parameters like injection pressure, lift speed and rotation speed. But also geometric uncertainties, such as the deviations of the verticality of the drilling and column diameter play an important role in the overall performance of the jet grout strut.
In order to assess the possibilities of jet grouting in the Eem Clay layer, in 1999 a trial test was carried out in Amsterdam - North (Van der Stoel, 2001). This test proved that 1,10 m diameter grout columns could be constructed with a strength of 5,5 MPa and a stiffness of 1800 MPa. During the contracting stage in 2004 it appeared that, due to fast technical developments, contractors were convinced that substantially larger diameters were feasible.
Considering the large stiffness enhancement (the E-modulus of the Eem clay layer was to be improved by a factor of over 100) it was decided to design a pattern of overlapping grout columns in a triangle pattern. The overlap is necessary to obtain sufficient overall stiffness and to guarantee good transfer of loads through the strut. However, a too large overlap may cause a "fault boring", when a new column is drilled into the edge of an older column, resulting in the absence of a full grout body. At 33 m depth, deviations may become too large to meet both requirements. Therefore, it was decided to accept that adjacent columns would occasionally not touch, as long as alternative ways of transferring loads were available. A column diameter of 2,2 m was selected with a centre to centre distance of 1,8 m. The distance of the column centre to the D-wall side is 0,85 m. It was assessed that with this configuration, the probability of a "fault boring" would be negligible. Shadowing (drilling close to an existing column, resulting in an incomplete column) could not be ruled out, but the consequences have little impact for this purpose.

Monte Carlo Analysis
The geometrical performance of the grout columns was simulated using a Monte-Carlo analysis. Input parameters were column diameter, surface location and inclination of the drilling pipe. A

section with a length of 1/10 of the station box was selected, this section was calculated 1000 times, so in fact 100 runs cover the whole station. The input parameters are listed in Table 2.

Table 2 - Geometrical input parameters for Monte Carlo Analysis

Parameter		**Mean**	**Deviation**	**Distribution**
Location at surface	x, y	Grid value	0,02 m	Normal
Angle, deviation from vertical	i	0,55%	0,24%	Lognormal
Depth	L	32 m	-	-
Diameter	D	2,3 m	0,10 m	Normal

- The deviation from the theoretical grid on ground level was determined on basis of the expert opinion that in exceptional cases (1%) deviation of more than 0,05 m would occur.
- The deviation of the drilling angle from the vertical axis was based on experiences in other projects. It means that the contractual value of 1% would be exceeded in 4% of the columns.
- The diameter parameters were based on the assumption that 14% of the columns would not meet the contractual requirement of 2,2 m. The relatively small deviation is based on the fact that the column is made in a single, homogenous soil layer.

The spreadsheet model generates the co-ordinates of gaps in between grout columns. Figure 2 shows a typical result. The gap co-ordinates were automatically transferred to a 2D FEM (DIANA) plate model. The boundary conditions of this plate, i.e. the loads and springs, were derived from a 2D FEM (PLAXIS) model (Figure 8). The loads depend on the strut stiffness. The relation between the strut load and the horizontal displacement of the D-wall is determined by varying the elasticity modulus of the grout strut in the PLAXIS model. At the end of excavation, the average stress in the 1,5 m high grout strut is 1,5 - 2 N/mm2. Bending moments, due to swell induced upward forces, result in an additional stress of +/- 0,5 N/mm2.

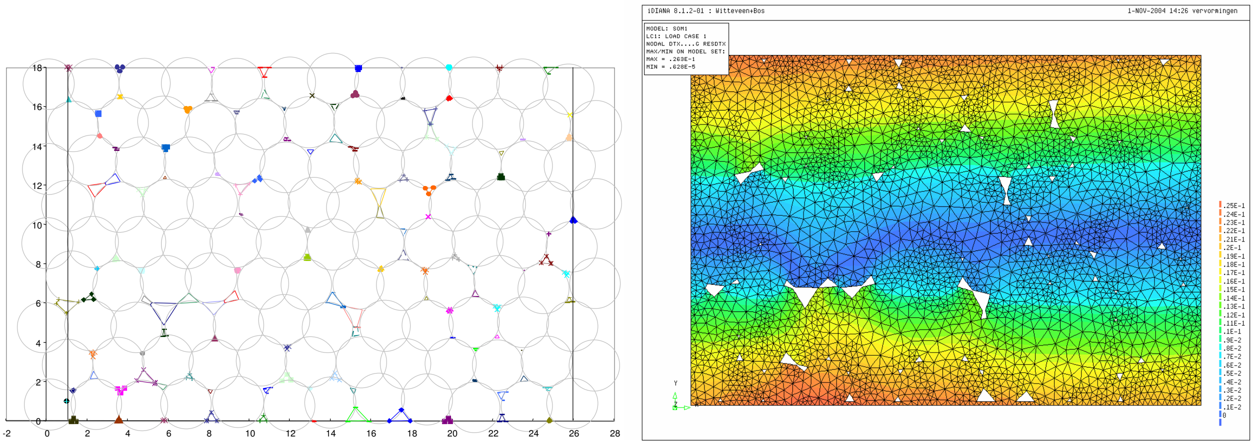

Figure 2 - result of gap generator (l) and resulting deformations in FEM plate model (r)

The reduced stiffness was calculated for 1000 random generated gap configurations. The gap reduction factor is 0,93 on average, with low (5%) and high (95%) boundaries respectively 0,87 and 0,95 (Figure 6, red dotted line).

Material properties

Several trials were carried out in the Ceintuurbaan station box. From these tests it followed that a cement content of 550 kg/m3 would lead to acceptable values for strength and stiffness.

During the construction, cores were taken from the station box in order to check the jet grout quality. In total 148 tests were carried on cores of 50 mm diameter and 50 mm height to determine strength, stiffness and density, according to DIN 181-36E. Figures 3 shows the results.

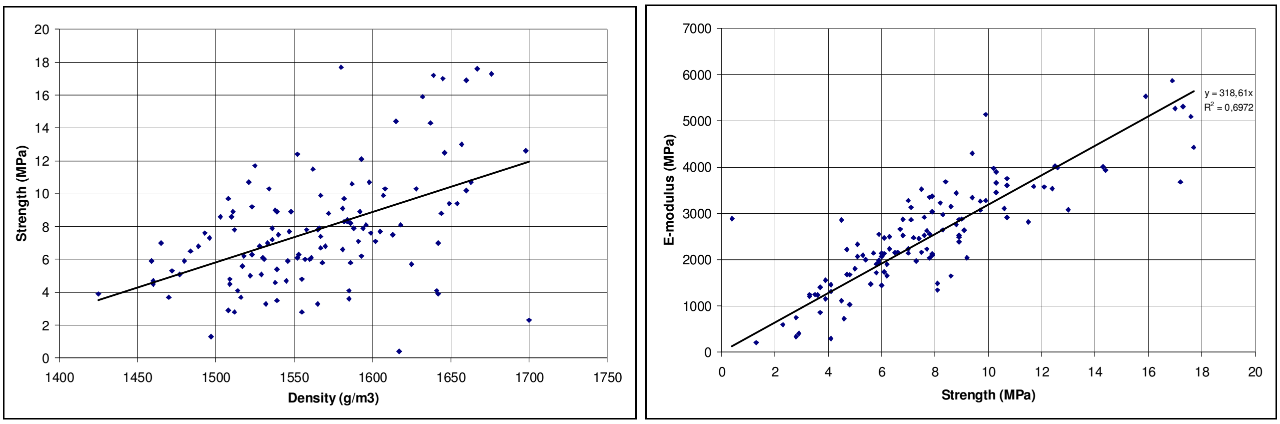

Figure 3- Unconfined Compressive strength vs. density and Unconfined Compressive strength vs. stiffness

The age of the jet grout at date of testing ranges from 19 to 154 days. Strength and E-modulus show no clear development in this range of time. Both strength and stiffness show a clear relationship with density. The relation between stiffness and strength is well defined by E/fc = 320.

Creep tests

The long-term deformations were determined by creep tests. 14 cores were sealed and loaded during 100 days under a uni-axial load of 2, 5 and 8 MPa. Cores with diameters of 33, 50 and 100 mm were used, all with a height/diameter ratio of 2. The age of all cores at time of loading was approximately 100 days. Dummies were prepared under the same condition in order to assess the amount of shrinkage and other external effects.

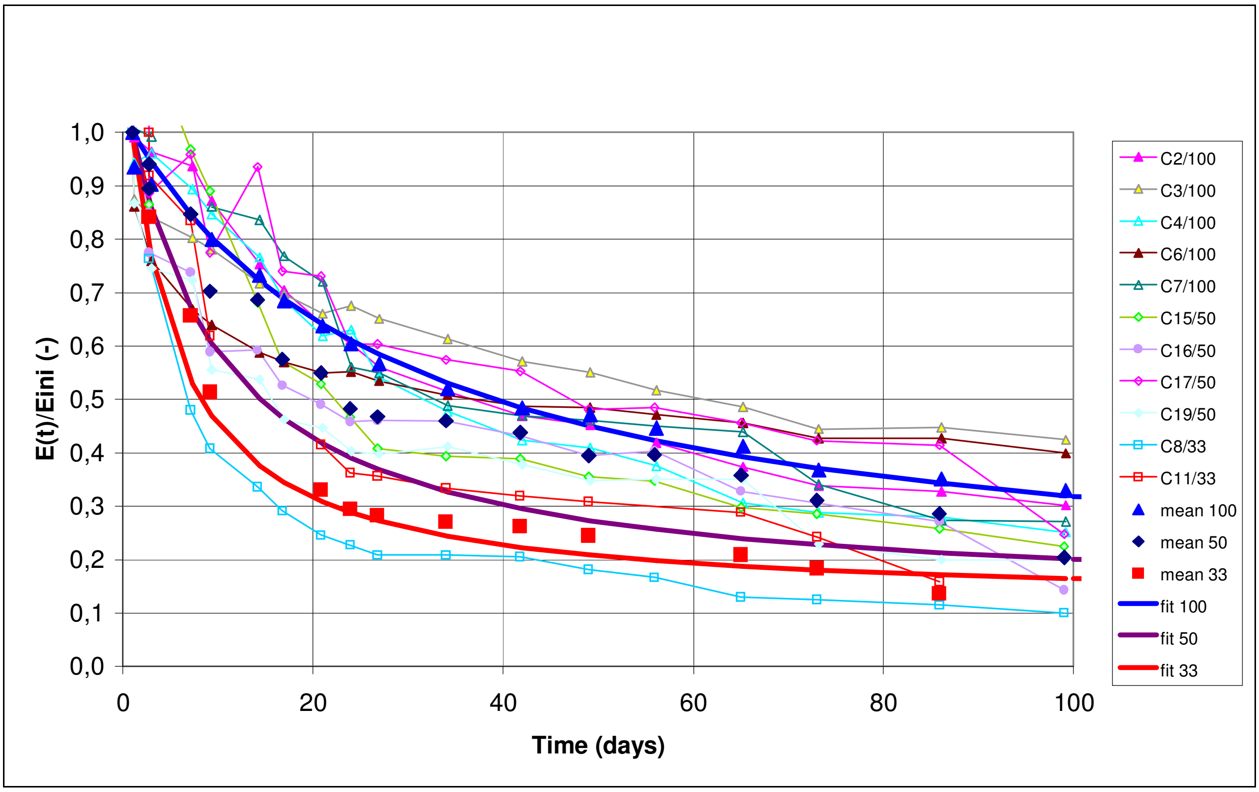

Figure 4 - Normalised stiffness vs. time

Figure 4 shows the ratio of the normalised stiffness: $E(t)/E_{initial} = \varepsilon_{el} / (\varepsilon_{el} + \varepsilon_{vis})$. The graph shows substantial creep deformations that continue even after 100 days. At the end of measurement, the E-

modulus is reduced to 10-40% of the initial value. The dummy measurements show that, despite the sealing, some shrinkage occured, but it was limited to 5-10% of the measured deformation due to loading.
It was expected to find larger creep numbers at higher loads (Kudella, 2003), but no significant relation was found. At two cores, the load was raised from 2 to 5 MPa. The increase in both elastic and viscous deformations was proportional to the load increase.
The dimension of the cores seem to be of influence: the strain in larger cores (D=100 mm) is substantially smaller than in smaller cores (D=33 mm). Also, the creep rate directly after loading appears to be lower.
This raised the question what creep could be expected in a 1500 mm buried grout strut. In terms of concrete, the effect of size is usually related to shrinkage. The seepage theory states that shrinkage and creep are closely related and that the origin of both lies in the transport of gel water under load (either due to a gradient in vapour pressure or an external load) from the gel pores to the outside. At the same time the load is transferred from the gel water to the cement paste. The seepage theory does not fully explain creep behaviour of concrete, but has some similarity to what soil mechanics call consolidation or primary compression.
The relation between creep deformation, time (days) and equivalent radius (mm) can be fitted quite well by the following relation:

$$\frac{E_i}{E(t)} = 1 + 7{,}5\left(\frac{t}{t + 0{,}98 \cdot r^{3/2}}\right)$$

This relation fits very well for the 100 mm cores, and reasonably well for the 33 and 50 mm cores (Figure 4). When this relation would be valid for the grout strut size (r = 750mm), almost no creep is to be expected in the time range of functioning (approx. 1 year).

Observational method
The uncertainties result in a relatively wide prediction range of the overall performance of the grout strut. Therefore, it was decided to build in some flexibility in the design by introducing the observational method. The grout column pattern was divided in blue, green and red columns. Blue columns are test columns. The basic design consists of blue and green columns, which are sufficient in case of a high overall stiffness (high E-modulus, low creep, high geometrical performance). If it would appear that the overall stiffness was near the lower boundary, the orange and red columns could be made in a later stage of excavation. Semi-probabilistic FEM-calculations showed that this would increase the stiffness by approximately 40 to 90 % respectively (Figure 6). The deformations were monitored continuously through a system of inclinometers, tell tales and robotic total stations.

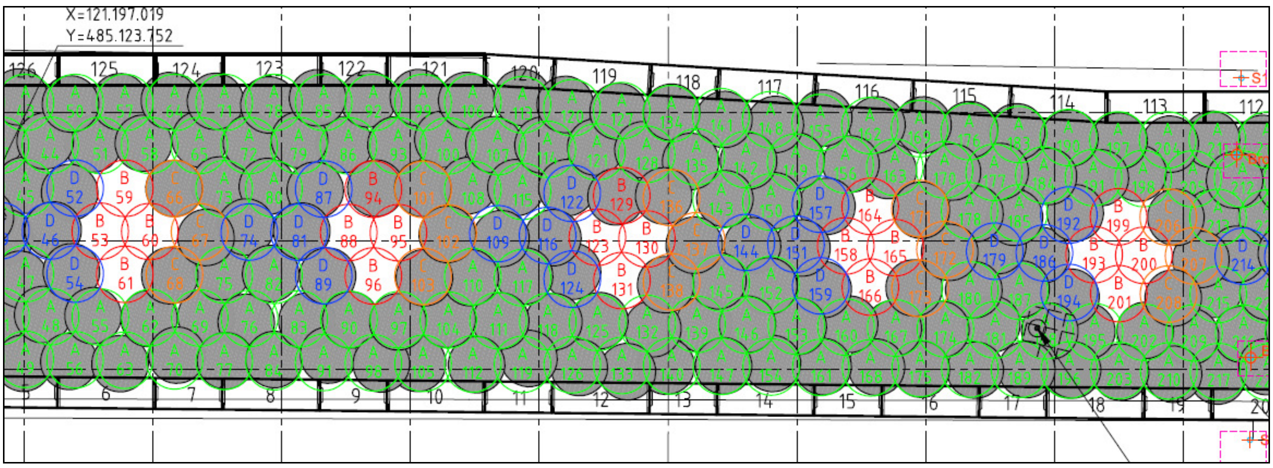

Figure 5 - Fragment of column design (green, red and blue circles) and as built (grey fill)

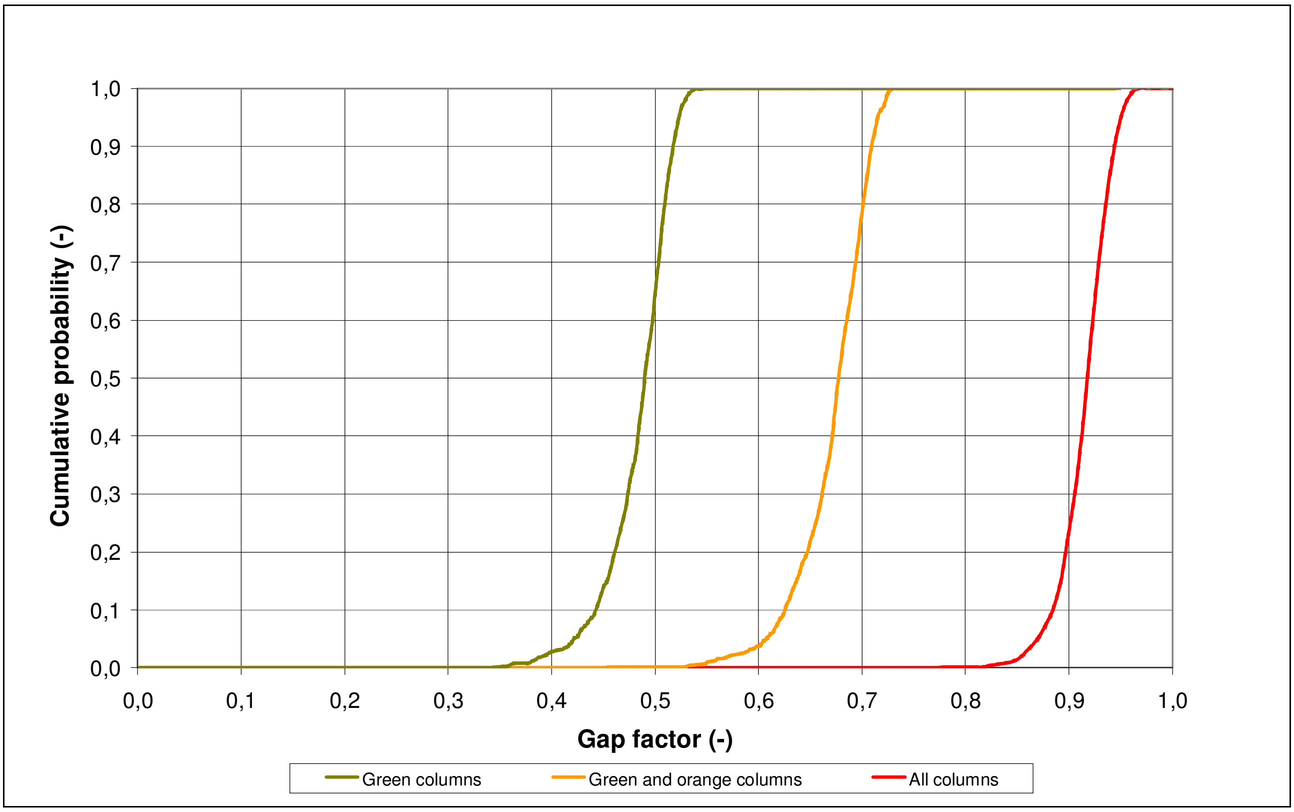

Figure 6: cumulative probability of gap reduction factor from 1000 MC/FEM calculations for three column configurations

EVALUATION

Construction stage

Ultimately, all green and orange columns were constructed. In total, over 700 columns were made in a period of 5 months, including the testing program period. The testing program was aimed at finding the process parameters that would lead to the required cement content and column diameter. Diameters were checked by the hydrophone method.

At the Ceintuurbaan station box, the contractor measured the verticality of all drillings. This created the possibility of adjusting the position of columns in case of large deviations of earlier produced columns. This was not necessary, because the verticality was well within the contract demand (1%) and on average (0,40%) lower than expected (0,56%). Soe adjustments were made, but only at locations were obstacles were met or in case of failed columns.

The influence of the construction process is clearly illustrated by the inclinometer measurements. The inclinometers are placed in the heart of the D-walls. Figure 8 (right graph) shows that, at the level of the strut, the D-wall deflects about 3 mm outward due to the construction of the grout strut. This effect is also mentioned by other authors (Hsii-Sheng Hsieh, 2003) and is probably caused by high injection pressures during the process of pre-cutting and grouting. Above the strut, an equally large inside movement of the D-walls is measured. This effect can largely be explained by the weakening of the soil body exposed to erosion by the return fluid (spoil). The spoil columns were much larger than expected (Figure 7) and this most likely reduced the initial horizontal soil stress. This assumption is supported by the results of CPT's before and after the drilling. The average cone resistance in sand layers dropped by 35%. The presence of large spoil columns complicated the excavation works.

Figure 7 - Spoil columns waiting to be transported

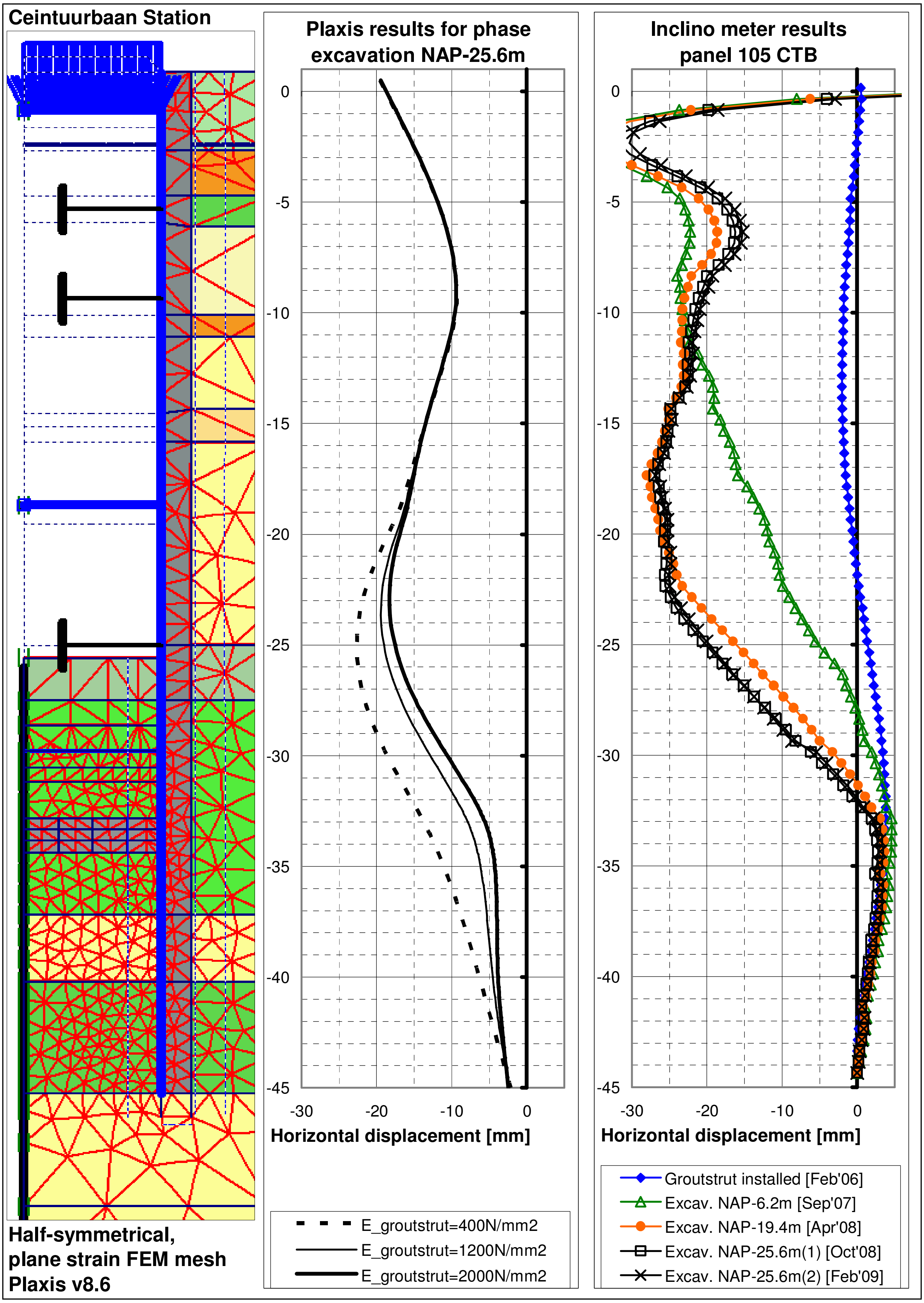

Figure 8 - FEM Mesh, calculated and measured horizontal displacements of diaphragm wall

Excavation stages
The inclinometer measurements of October 2008, when the excavation reached a level of 25 m, show that the D-wall moved only 2-3 mm inward since construction of the grout strut. This deflection needs correction, since FEM calculations show that at toe level of the D-wall, still 2-3 mm of movement is to be expected. So in total, the inward D-wall movement at the strut level (dx) due to excavation is 4-6 mm. The actual stiffness can be assessed by the formula:

$$E_g = \frac{\sigma \cdot L/2}{dx \cdot f_{gap}}$$

The average stress (s) in the grout strut, according to FEM calculations, is 1,7 N/mm2. The length (L) of the grout strut is 11 m. The gap factor (f_{gap}) is 0,61-0,77. This indicates that the mean E-modulus of the jet grout ranges from 2000 to 3800 Mpa, which is in the range of the initial elastic E-modulus. This indicates that creep effects are negligible. The measurements of February 2009, 4 months after reaching the deepest excavation level, show no extra movement at all and thus further indicate that creep effects are not significant in these conditions.

CONCLUSIONS
Despite many uncertainties, it proved possible to design and construct a jet grout strut in the Ceintuurbaan station that fulfils the requirements. Monitoring and the possibility of design adjustments during the construction phase are important success factors.
From inclinometer measurements, the overall performance of the grout strut could be evaluated. It appears that the stiffness is near the high boundary of the prediction. This indicates that, in these circumstances, creep effects are negligible.

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