FIELD MEASUREMENTS OF GROUT PRESSURES DURING TUNNELLING OF THE SOPHIA RAIL TUNNEL

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ABSTRACT

During drilling, grout pressures were recorded on a tunnel lining measuring 9.5 m in diameter. Two tunnel rings were fitted with pressure gauges (14 gauges per ring). Measurements were performed for more than one day. Final hardening of the grout did not occur during this time. The lowest pressures were measured at the start of the drilling process after completion of the ring. Results show that the grout pressure distribution is dominated by injection during drilling, but this distribution changes when drilling stops and buoyancy forces start to exert an influence. The influence of buoyancy forces increases further away from the injection points. Bending moments in the tunnel lining also influence the gradient in the grout pressure distribution.

Key words: grouting, lining, monitoring on site, rheology, shear strength, shield tunnelling method, vane shear test (IGC: A10/C5/E3/K2)

INTRODUCTION

Since 1996, the Centre for Underground Construction (COB) in the Netherlands has initiated a substantial amount of practically-oriented field and desk research (Bakker et al., 2001). One of the main issues in this research was settlement control and its prediction. As pressure control at the front of slurry type TBMs is generally properly controlled nowadays, the focus must now be on improving process control for backfill grouting in the annular tail void in order to increase settlement control. Research findings so far have shown an evident qualitative correlation between the quality of the grouting process in the annular tail void at the back of the TBM, and settlements. However, this correlation has not yet led to a quantified relationship. With plans underway to construct a metro tunnel under Amsterdam's historic city in coming years (Kaalberg et al., 2001), the autonomous government policy for ongoing tunnelling research is given additional support.

COB therefore took the decision to define additional field and desk research at the Sophia Rail Tunnel (4.2 km twin bore tunnel, external diameter 9.5 m). One of the main objectives of this research is to increase knowledge about the injection, flow and hardening process of the backfill grouting to obtain a more constant, reliable and predictable settlement control for future projects in urban environments worldwide.

Another main research topic is the behaviour of the

tunnel lining during construction. Damage occurring at segmental joints is sometimes seen, originating primarily from joint design but presumably also from fluid grout loads in the annular tail void.

To tackle both these issues in a single field research project, two complementary ways of monitoring the grouting process were defined. The grout pressures at the back of the TBM were measured continuously, and one cross section was defined where building, surface and subsurface instrumentation are installed. Two tunnel rings (one in each tube) are also circumferentially fitted with grout pressure sensors in the lining.

The aim is to instantaneously analyse the grout pressure distribution around the tunnel, both behind the TBM and at a greater distance. This information will later be used as input to further calibrate and validate earlier developed 4D FE models (van Dijk and Kaalberg, 1998) for settlement prediction and lining calculations.

In this paper, the monitoring data of lining sensors for the first and second TBM passage are described and analysed, and grout pressures are calculated using a grout flow model.

THE SOPHIA RAIL TUNNEL

The Sophia Rail Tunnel is one of three bored tunnels along the Betuwe route. It consists of two single rail tubes with an outside diameter measuring 9.5 m, and a concrete lining with a thickness of 0.4 m. The tunnel crosses three

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Fig. 1. Cross-section of the Sophia Rail Tunnel and soil layering at the measurement location

polders and the River Noord (a branch of the River Rhine), and is located some 20 km southeast of Rotterdam. More information on the location of the tunnel and its design features can be found in Stive (1999).

The tunnel section where the measurements were performed was situated in the IJsselmonde Polder west of the River Noord, where the tunnel is at a constant depth. The polder is an agricultural area. A few houses are located close to the tunnel trace and the measurement location. These houses do not have deep foundations and have no influence on the tunnelling process.

At the location where the measurements were carried out, the 12-m-thick Holocene top layer consists of peat (2/3) and clay (1/3). The distance between the tubes is 10 m. Underneath the top layer is a medium density sand layer of Pleistocene sand measuring 10.7 m in thickness. Underneath this sand layer is the Kedichem layer, which consists of a layer of peat and silty clay at the measurement section. A cross-section of the tunnels and the soil layers is shown in Fig. 1. Surface settlements were measured at various locations in the same cross-section where the instrumented ring fitted with grout pressure transducers was placed. Piezometric head was measured using pore water transducers (see Fig. 1 for the locations). The piezometric head appeared to be at the same level at different depths, approximately 1 m below the ground surface. The measured fluctuations in the piezometric head were less than 5 cm before drilling started. The overburden pressure at the crown of the tunnel is approximately 200 kPa.

The measured surface settlements above the instrumented ring were limited to less than 5 mm. At some locations, there were even a few millimeters of heave.

THEORY

Before hardening, grout can be described as a Bingham liquid. However, its properties change with time. Viscosity and yield stress increase. Talmon et al. (2001) presented a flow model describing the pressure distribution around a tunnel lining caused by grout flow, and as a function of the discharge through the injection points.

However, a Bingham liquid can withstand shear stresses without flow (whereas a Newtonian fluid cannot). This means that also without flow, the hydrostatic pressure

Fig. 2. Scheme to calculate the pressure distribution due to buoyancy forces

distribution is not necessarily present. In the case of grout around a tunnel lining, the lining will move upwards due to buoyancy forces. It can only move if the grout is pressed down. This will be prevented by the shear stresses between the soil and the grout. From our experiments and analysis of field measurements, Talmon et al. (2001), we have concluded that the shear stress between concrete and grout is much smaller than the shear stress between soil and grout. The former can therefore be neglected. The relationship between shear stress and pressure caused by that shear stress can be derived from Fig. 2, and results in:

$$\Delta P = \tau \frac{R}{s} d\alpha \quad (1)$$

where ΔP is the pressure change caused by the yield stress τ , R is the radius of the hole made by the tunnel, s is the thickness of the grout layer, and α the angle indicated in Fig. 2. Assuming that the grout flows to the bottom of the tunnel from a location with a certain angle α , the total pressure drop by the yield stress is:

$$P = \tau \frac{R}{s} \alpha \quad (2)$$

This excess pressure that increases with α will result in a downward directed force on the tunnel. This compensates the buoyancy force K . For a small segment, it can be written as:

$$dK = PR \cos \alpha d\alpha \quad (3)$$

Combining Eqs. (2) and (3) and integration over the two half circles leads to:

$$\tau = \frac{K_s}{D^2} \quad (4)$$

Using this last equation, it is possible to calculate the yield stress that must be present to prevent upward movement of the tunnel lining until it touches the ceiling of the hole drilled due to buoyancy force.

If the actual yield stress τ is larger than the result of Eq. (4), then there will be only limited movement of the

Fig. 3. Distribution of pressure sensors in the lining and grout injection points on the TBM (with codes used in the graphs)

tunnel and Eq. (2) using the result of (4) gives the influence on the pressure distribution. Without shear stress, the pressure will increase according to a hydrostatic pressure distribution. Equation (2) leads to a pressure that is highest on top of the tunnel, and which thus counteracts the hydrostatic pressure. The resulting pressure gradient will therefore be less than the hydrostatic gradient.

MEASUREMENT PROCEDURE

Several segments in one tunnel ring consist of an instrumented ring where pressure sensors were installed. The positions of the sensors in the ring are shown in Fig. 3.

These pressure sensors in a stainless steel housing (see Fig. 4) were permanently positioned using epoxy resin in holes drilled in the concrete segments. They can be used for measurements even after initial pressure monitoring. Before installation and measuring, a complete system test and calibration was carried out. One segment underwent a competency and waterproofing test by applying a pressure of 1 MPa for 24 hours. The remaining segments consequently underwent a competency and waterproofing test by applying a pressure of 0.25 MPa for 2 hours.

The pressure sensor is the Labom type DE1680-A4001-L19, with a measuring range of 1 MPa and an accuracy of 0.25% full-scale (2.5 kPa). The sensor consists of a flat membrane (50.8 mm diameter) placed on its outer surface. The membrane is placed 4 cm below the outer surface of the segment to prevent damage by the steel brushes at the end of the TBM shield as it passes by. To prevent airlocks, the space above the membrane is filled with the same grease used to seal the tail end.

During the measurements for the first tunnel tube, the sensors were sampled at 25 Hz. The relatively high frequency sampling of 25 Hz was used to measure possible high frequency events. Analysing the data, including Fourier transform, showed that such events were not present in the measurements. Therefore, a considerable data reduction of 1 of 500 samples could be used without

Fig. 4. Cross-section of pressure sensor as mounted in the lining during the experiments

Fig. 5. Outline of data measuring system (only 3 of the 14 sensors are shown)

loss of significant data. During the measurements for the second tunnel tube, the measuring frequency is reduced to 2 Hz.

The data acquisition system is based on an internal PC card (Keithley, DAS, 1802). This card controls the sensors and collects and archives the measured data. The internal PC card is connected to a signal conditioning box on which the sensors are connected. To reduce the risk of losing measurements, each sensor is connected to the signal conditioner box with a separate signal cable (instead of a bus system where one cable is used to connect all sensors). While the measurements are being taken, the results are presented online on a computer display in a graphical and tabular form. The measurement system used is shown schematically in Fig. 5.

Data is recorded while the segment is still within the TBM shield. Measurements are continuously logged for 15 hours during the first phase, and for 30 hours during the second phase.

RESULTS

Pressures Versus Time and Versus Displacement

Measured grout pressures are shown in Fig. 6 as a function of time together with the drilling velocity. The grout pressure is shown with respect to atmospheric pressure.

Fig. 6. First tunnel tube: drilling velocity and measured grout pressures at the right side of the tunnel as a function of time

The pressure is initially zero when the sensors are still in the TBM. Just before 06:00, the pressures become rather irregular as the instruments pass through the grease and brushes at the tail end of the TBM. There is a pressure jump at 06:00 as the instruments arrive in the tail void and the grout pressure is measured. This figure shows that grout pressures increase during drilling when grout is injected, but decrease during periods of standstill (probably due to dewatering of the grout into the soil).

Only half of the instruments are shown because the number of lines would lead to confusion if results from all the transducers were shown. Just before 05:00, the grout pressure transducers pass through the first tail brush. At approximately 06:00, they reach the grout. After completion of drilling for that ring, the grout pressures decrease until drilling for the next ring starts at approximately 07:30. The segment width of a tunnel ring in the longitudinal direction of the tunnel is 1.5 m. In the decreasing pressure, a sharp rise or fall in pressure can be distinguished. Analysis of the measurements showed that this was caused by the ring building process. The rise or fall could be associated with movement of the plungers of the main jacks whilst the tunnel lining segments were being positioned.

What is remarkable is the dip in grout pressure, measured by all transducers just before drilling for a new ring started. The reason for this dip can be seen in Fig. 7. This figure shows the drilling velocity and the number of strokes of the grout pumps per second as a function of displacement in the upper plot. It can be seen that when

Fig. 7. First tunnel tube: drilling velocity, strokes per second of the grout plunger pumps, and grout pressures as a function of the displacement (a moving average over 25 points was taken for the data on the plunger pumps to reduce data noise)

drilling started (the velocity jumps from zero to a certain value), the grout pumps do not start immediately. The first drilling is therefore carried out with too little grout, leading to a sharp decrease in the grout pressure. Once the pumps started, the grout pressure increases again.

Polar Plots and Gradients

Figure 8 shows the measured pressures at different times in a polar plot, and the distribution of pressures as a function of height. Actual drilling took place at 06:19:30 and 08:00:00, and there was standstill for the other points. The measurement time is presented, together with the time since the pressure transducers started to measure grout pressures (shown in brackets). Both plots showed that the pressure distribution is as expected. The pressure increases more or less linearly with depth. The pressure distribution is virtually the same on both sides of the tunnel, although there is some difference between both sides for the 07:00 measurement. What is remarkable is that the pressure gradient in the vertical direction is not constant in the measurements. The slope of the line in the lower plot of Fig. 8 changes with time. The results shown in this paper are from measurements taken in one ring. This means that after installation, the same grout will be present during the measurement. If only the hydrostatic pressure in the grout determines the pressure distribution, then the

Fig. 8. First tunnel tube: polar plots and pressure as a function of height at various time intervals. The lower plot also shows the water (pore) pressure and the hydrostatic pressure in the grout starting from 2 bar at the top as a reference

gradient should be constant. However, more aspects play a role (see Section Theory) and will be elucidated further in Section Discussion. To investigate the gradients which did occur, the pressure gradient in the vertical direction was calculated using the least square method over all measurement points. The results are shown for the first tube in Fig. 9, together with pump activity by the pump for grout injection line A1 (the pump for A1 was selected to be reference when the pumps are on, although another pump could also have been chosen). The results show that the vertical pressure gradient generally decreases in time, and thus also as the distance between the TBM and the instrumented ring increases.

It is noticeable that up to 12:00 when drilling starts (and therefore activity from grout pump A1), there is a sharp increase in the pressure gradients when drilling commences. There is a decrease for the last rings. Possible explanations are dealt with in Section Discussion.

The gradients were also determined for the second tunnel tube. The results for this tube are shown in Fig. 10. For the second tunnel tube, it was possible to take measurements over a longer period where more tunnel elements were placed. The date is also given because the measurement was performed over a two-day period. The results from this second tube were closely comparable to the results from the first tube, although the gradient resulted in even lower values. This will also be dealt with in Section Discussion.

Fig. 9. First tunnel tube: pressure gradient over the tunnel lining at one location, and pump activity for one of the injection points (A1) as a function of time

Fig. 10. Second tunnel tube: pressure gradient over the tunnel lining at one location, and pump activity for one of the injection points (A1) as a function of time (upper plot). Momentum in vertical direction that is exerted on the lining by the plungers in the TBM (lower plot). A positive momentum means that the forces on the lower part of the tunnel are higher than on the upper part

GROUT RHEOLOGY

The rheological properties of the grout are an important factor with respect to backfill grouting. The grout has to distribute uniformly around the tunnel lining, and has to provide resistance against uplift forces further behind the TBM. Grouts are basically hyper-concentrated two-phase solid-fluid mixtures, where fine cement, fly ash and other additives lower the permeability of the grout. Essential parameters characterising the flow properties of grouts are yield stress and viscosity. Modelling as a Bingham fluid suffices. The yield stress is the governing parameter in the tail void because of small flow velocities.

The time-dependency of the yield stress has to be accounted for when back-filling. The yield stress of fresh grout mortars is typically in the range 1–3 kPa. This relates to failure of the grout interior. Workability of mortars is typically four hours.

The grout used at the Sophia Rail Tunnel is a grouting mortar made in accordance with specifications. With respect to frictional properties, the experiments described in this section showed that a distinction can be made between flow along smooth impermeable boundaries, and flow of pressurised grout along granular soil: along smooth impermeable boundaries, the flow of grout encounters little resistance (pipes, flexible hoses). This is due to the occurrence of a tiny lubricating liquid film.

Along soil boundaries, the friction is higher and is of the same order as the yield stress (this is our conclusion after analysing measured grout pressure distributions in tunnelling projects: Bezuijen and Talmon, 2001 and Talmon et al., 2001). A lubricating liquid film cannot develop as the grout pressure is higher than the pore pressure of the soil around the tunnel, and the liquid flows into the soil. As a result, the shear stress remains high and is governed by the internal failure mechanism of the grout.

Grout was collected from the production facility for rheological testing. The samples were taken just before the grout was sent to the TBM. The yield stress of the grout was determined by vane testing. The results of a number of consecutive vane tests on one sample are given in Fig. 11. The rotational speed of the vane is given on the abscissa. The measured shear stress as measured with a rotoviscometer (Haake M1500, vane FL10) is shown on the ordinate of the graph. In the first part of the experiment, the rotational velocity of the vane increases linearly with time (from zero up to 0.05 rad/s in 1 minute). During this part of the experiment, the stress increases until a peak is reached. A breakdown of the grout's internal structure then commences because a slip plane is produced. This peak represents the shear stress required for characterising the yield stress at the grout-soil interface. In the second part of the experiment (when the rotational speed remains constant for 5 minutes), further breakdown of the internal structure in the slip plane occurs. In the third part of the experiment (when the rotational velocity decreases linearly to zero within 1 minute), the shear stress is constant. This shear stress is representative for the flow along smooth surfaces, such as the tunnel lining and pipe walls (the slip plane produced by the vane is smooth).

From Fig. 11, it can be concluded that the final set of grout (hardening) commences after approximately 5.5 hours. After this time, the yield stresses increase quasi-linearly with time. During the first period of the final set (shown in Fig. 11), the grout still has fluid-like properties that are quantified by increased rheological properties. In this case, the final set commences close to finalisation of drilling of the second ring following grout injection (transit of the grout from the production facility to the TBM takes about one hour).

Fig. 11. Registration of shear stresses measured by vane testing, peak values applicable to grout-soil interface, lower values applicable to grout-lining interface

Another way to obtain data on friction with smooth surfaces is by pipe-viscometer testing. The flow resistance of back-fill grouts was measured in a pipe-viscometer with an inner diameter of 100 mm (Talmon et al., 2001). A range of grout flow velocities (2 mm/s–100 mm/s) was tested. The smallest velocity is comparable to the advance rate of the TBM. Such velocities are expected at some distance from the injection openings. In the immediate vicinity of the injection openings and in the supply pipelines, the velocities are approximately two orders of magnitude larger.

An example of results from one of the test series is given in Fig. 12. It concerns the flow of grout mortar in a smooth pipe, fitted with pressure gauges. The graph depicts the results for the wall shear stresses obtained from different pairs of pressure gauges, together with the root-mean-square values.

The results show that wall shear stresses are an order of magnitude smaller than the yield stress of grouts. It can be concluded that a lubricating film has formed along the wall, the rheology of which will be governed by cement-like fluid in between the coarse grains of the grout. Consequently, such tests only produce data on flow resistance between the lining and the grout, and of course in supply pipes. The latter is important, because grout pressures in most TBMs are monitored using pressure gauges mounted on the supply lines.

Apart from hardening, the rheological properties of the grout can also be determined by fluid loss of the grout due to dewatering. Research is currently underway into ways of quantifying this dewatering and the influence on grout properties.

DISCUSSION

Total or Pore Pressures

When taking field measurements, it may be necessary to compromise between the ideal measurement location

Fig. 12. Example of data obtained from pipe-viscometer grout flow tests: portland-type mortar, smooth pipe, (see text)

and a location where the sensors can survive. Looking at the location of the membrane as shown in Fig. 4, two questions can be raised:

1. What is the influence of the grease between the grout and the membrane on the measurement results?
2. What is the pressure measured, a pore pressure or a total pressure?

Shear stresses that develop between the grease and the casing can influence the measurement results. However, we have no indication that this has happened. As can be seen from the measurement results, Figs. 6 and 7 also show small fluctuations that would not be present if the results were influenced by shear stresses. The stiffness of the casing and membrane is such that the pressure is transferred from the grout to the membrane without significant deformation of the grease. Such a deformation would be necessary before shear stresses can develop.

It is argued in literature that these relatively small pressure gauges only measure the pore pressures, and not the total stress. This particularly occurs when there has been some hardening of the grout. Special, relatively large sensors have been developed to measure the total stresses (Hashimoto et al., 2002). However, the sensors used in the field tests described in this paper also measure total stresses. Due to the viscosity of the grease, it cannot penetrate into the grout along the grains of the grout. The stress on the grease is therefore the pore pressure exerted by the pore fluid and the grain stress exerted by the grains, i.e. the total stress. There was no bridging of the grout grains (which would lead to a lower effective stress near the sensor than elsewhere in the grout) due to the stiffness of the measurement device. If the pressure gauges only measured the pore pressures it would be impossible to measure a gradient lower than 10 kPa/m.

The arguments presented above are no real proof that the grease has no influence and that a total pressure is measured. This, however, was confirmed by the measurement results. The measurement results would be difficult

to explain if the grease had exerted an influence or if only pore pressures had been measured.

Pressures

At the location of the instrumentation, the estimated effective pressure on top of the tunnel lining was approximately 200 kPa (2 bar) (Bezuijen and Talmon, 2001). This is close to the grout pressure applied during drilling on top of the tunnel (instrument Bb in Figs. 6 and 7). When drilling stops, the grout pressures decrease. This decrease is largest at the pressure gauges at the lower part of the tunnel. This will be the reason that the reported settlements at this ring were only limited.

The lower plot in Fig. 8 shows that the grout pressures are above the pore pressures at that location, although the difference is only small for the last measurement (time = 16:59:52). It also shows clearly that the measured pressures are always lower than the hydrostatic pressure in the grout if a 2 bar grout pressure is assumed at the top.

Gradients

The grout pressure on top of the tunnel is an important parameter that influences the surface settlement. The vertical pressure gradient is important for understanding the grouting process, but together with the absolute pressure, also determines the stress distribution in the soil. The latter is important for understanding soil-structure interaction for adjacent foundations.

The volumetric weight of the grout used was 21.5 kN/m³. In case the hydrostatic pressure determines the vertical pressure gradient, the gradient should be 21.5 kPa/m. As can be seen from Figs. 8 and 9, this value is never reached during these measurements. A likely reason for this discrepancy are the buoyancy forces explained earlier. When there is also still a grout flow however, the pressure distribution will not be a hydrostatic distribution (Talmon et al., 2001). During drilling, the pressure distribution close to the TBM is governed by the grout flow from the grout injection points around the tunnel lining. If there is a downward directed flow, the pressure (corrected for hydrostatic pressures) has to decrease to maintain the flow.

The flow model described by Talmon et al. (2001) was used to simulate the grout pressures. The parameters used are summarised in Table 1. The density and rheological parameters of the grout were determined from samples taken from the construction site. The shear stress as determined with the vane tests was used to describe the friction between the grout and the soil. The result from the pipe flow tests was used for the friction between the grout and the lining. The distribution of grout injection flow rates over the six injection ports A1 to A6 (see Fig. 3) has been read from the strokes made by the grout delivery pumps (see Fig. 7). As a representative distribution, the following values were used: A1=0.2, A2=0.133, A3=0.133, A4=0.133, A5=0.2, A6=0.2, these values are relative to the whole flow rate, which is set to 1.0. Together with the flow resistance of the grout, this distribution governs the deviation of the pressure distribution.

Table 1. Parameters used in grout flow calculation

Parameter	Value	Dim.
Diameter lining ($D = 2R$)	9.45	m
Thickness grout layer (s)	0.16	m
Density grout (ρ_{gr})	2190	kg/m ³
Yield stress at grout-lining interface, at injection	0.1	kPa
Yield stress at grout-soil interface, at injection	0.8	kPa
Onset hardening, time since injection	4.5	hour
Hardening rate grout	0.4	kPa/h
Grout pressure at top	1.8	bar
Drilling velocity	7.2×10^{-4}	m/s

bution from hydrostatic. The vane-measurement results (see Fig. 11) revealed that the yield stress was 800 Pa up to a grout age of 5.5 hours. Once this age was reached, the yield stress began to increase. At an age of 7.5 hours, the yield stress was 1.8 kPa and increased with time. The input parameters of the flow model are listed in Table 1. The results are given in Fig. 13 and show close correlation with measurements obtained during drilling. In Fig. 13, the measurement legend shows the measurement time, the time elapsed since the grout pressure transducers entered the grout, and the distance to the back of the TBM. The distance to the back of the TBM is given for the calculations only. There is slight asymmetry in the calculation model. This results in a small pressure difference at 180 degrees in the calculated pressure in the polar plot. In the lower plot, this asymmetry results in two lines for each calculation (one for 0 to 180 degrees, and one for 180 to 360 degrees). This is an artefact of the numerical model only. The two lines are presented to show the accuracy of the solution procedure used.

The model described to calculate the influence of the buoyancy forces on the pressure distribution does not predict a constant vertical pressure gradient as measured. The gradient is assumed to be constant over the circumference (Eq. (1) showed that $dP/d\alpha$ is constant) and would therefore vary over the tunnel height. The maximum gradient is found at 90 and 270 degrees (see Fig. 8, upper plot). At these points, the gradient can be written as:

$$\frac{dP}{dz} = \rho_{gr}g - \frac{\tau}{s} \quad (5)$$

With ρ_{gr} the density of the grout and g the acceleration of gravity.

The additional parameters used in this calculation to calculate the gradient are presented in Table 2. The grout pressure at the top is now lower, because this pressure decreases when grouting stops.

Using these parameters, it can be calculated that the buoyancy force $K = 1239$ kN/m. Using Eq. (4), this results in a shear stress τ of 2.22 kPa between the soil and the grout. Using these results and Eq. (5), the maximum gradient is found to be 7.6 kPa/m if buoyancy forces only determine the gradient. This is less than the minimum gradient measured during standstill for the first tunnel tube (Fig. 9). Therefore, it can be concluded that

Fig. 13. First tunnel tube: measured and calculated grout pressures compared during drilling (see text)**Table 2. Additional parameters used in calculations**

Parameter	Value	Dim.
Thickness lining (sl)	0.4	m
Density concrete	2400	kg/m ³
Grout pressure at top	1.8	bar

the measured gradient for that tube is also influenced by moments in the lining as it is fixed by the TBM on one side and the hardened grout on the other. For the second tube where the measurement interval is longer (Fig. 10), the gradient during standstill is equal to the calculated buoyancy gradient.

These buoyancy calculations led to another result. The calculated shear stress is more than the yield stress measured (see Section Results). This means that the tunnel would not be stable and would be lifted by buoyancy forces. Another way to look at the results is to determine the yield stress in the grout from the measurements. If the rheological properties of the grout are the same as for water, the gradient would always be 21.5 kPa/m with or without drilling. Assuming that the tunnel attempts to move upwards due to buoyancy forces, the minimum measured gradient results in a mobilized shear stress using Eq. (5). This can be less than the yield stress, but not more. From using Eq. (5) it can be concluded that a measured gradient of 12 kPa/m around 08:00 (see Fig. 9) corresponds with a minimum yield stress of 1.5 kPa. The minimum in the gradient measured just after 12:00 of 7.6 kPa/m means that the yield stress is then 2.2 kPa or more. These values for the yield stress are higher than

measured with the vane. Possible reasons for these discrepancies are:

The rheological parameters are determined by atmospheric pressure. Dewatering in the field situation can lead to higher yield stress.

Based on flow experiments, the shear stress along the tunnel lining and the grout is neglected. It is possible that this changed in no-flow conditions.

From the measurements presented here, it appears too simple to state that the pressure distribution close to the tunnel is governed by the TBM and that buoyancy is dominant further away. The pressure close to the TBM is dominated by the grout flow during drilling, but is influenced more by buoyancy during standstill. The model presented on the buoyancy is purely 2-D. It only takes one ring into account and not the possible bending moment along the tunnel axis. This appeared to have a substantial influence close to the TBM. Further away from the TBM, however, the influence of the bending moment in the lining decreases during standstill and the gradient approaches the value calculated with Eq. (5).

During actual drilling, the gradient is highest in the first lining elements that were placed after the instrumented ring. When the TBM is further away from the instrumented ring, however, the gradient is lowest during drilling. These low gradients can be seen around 12:00 and 14:00 for the first tunnel tube, and for the lining elements placed at 28:00:00 hour and later for the second tube (see Figs. 9 and 10). The high gradients in the grout pressure close to the TBM are caused by the injection strategy. An even distribution of grout over the lining will lead to a hydrostatic pressure distribution. There was no even distribution here as more was grouted to the top than to the bottom (see Fig. 6). The pressure gradient was therefore slightly smaller than according to hydrostatic pressure. As distance increases from the TBM, the grout flow has virtually no influence on the pressure distribution. Buoyancy forces will be dominant for the pressure gradient in the grout, as well as forces exerted by the TBM on the lining, which can lead to lining movements and consequently a change in the pressure distribution e.g. if larger jack forces are used in the bottom part of the TBM to compensate for a tendency to penetrate too deeply because of its weight. These forces will induce a moment in the lining and will lead to lining movement until the pressures on top of the lining have increased to compensate for this moment. This latter effect leads to the extremely low pressure gradients measured during actual tunnel drilling. This is also shown in Fig. 10. The lower plot shows the momentum exerted by the TBM on the lining. This momentum is calculated using the pressures and positions of the 28 main hydraulic plungers used to push the TBM forward against the lining during drilling. The result is presented on the same time scale as the gradient in the upper plot. The plot shows that the momentum increases by drilling, meaning that larger forces are used at the lower half of the tunnel than on the upper half. It can be seen from the plots that a change in momentum does not directly influence the gradient in the grout pressure,

but if the change is present over some time (as is the case during drilling), it will influence the grout pressure gradient.

CONCLUSIONS

The grout pressure measurements presented in this paper and comparison with calculations lead to the following conclusions:

1. Reliable measurements were obtained for the grout in the liquid phase and the start of the hardening phase. Measurements were taken over too short a period to provide data for the whole hardening phase of the grout. It is also uncertain whether the instrumentation used would survive the hardening phase.
2. It is likely that total stresses were measured, and this corresponds with the measurement results.
3. The grout pressures are not only influenced by the injection strategy and flow, but also by forces exerted on the lining during placing of segments or drilling.
4. Drilling commenced before start of the grout injection pumps. This led to a decrease in grout pressure at the start of drilling. This pressure decrease could be measured up to 5 m behind the TBM.
5. Injection strategy can influence the pressure distribution close to the TBM (< 5 m) during drilling. During standstill and further away from the TBM, buoyancy forces and bending moments in the lining govern the pressures. This results in pressure gradients considerably lower than those determined according to hydrostatic pressure distribution in the grout.

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