ABSTRACT: Functions of tail void grout are described and necessary properties of the grout mortar to fulfill these functions are discussed. A simple model is derived to show the loading on the lining along the axis of the tunnel as a function of the mortar properties and the possible movement of the lining. When it takes a long time for the grout mortar to consolidate or to harden, resulting in buoyancy forces on the lining over a certain length, this can lead to considerable forces in the lining of a tunnel as well as on the TBM. This is shown with some indicative example calculations, for conditions measured in 2 projects and 3 different grout mortars.

1 INTRODUCTION

Back-fill grouting is a crucial process in TBM tunnelling. The grouting process determines the loading on the soil and with that an important part of the surface settlement. It also determines the loading on the lining. Field and laboratory measurements (Bezuijen et al. 2004, Bezuijen & Talmon, 2003) have revealed mechanisms that are of importance: the flow of the grout around the tunnel, the yield stress that determines the maximum resistance against the buoyancy forces and the influence of consolidation of the grout on the loading on the lining. The parameters necessary to describe these mechanisms are not given in the traditional grout tests and therefore a new test was developed.

The paper describes the functions of grout during and after injection in the tail void. A calculation method is presented that gives an indication about the loading along the lining. This calculation method is compared with the results of measurements for 2 tunnels and 3 different grout mortars.

2 FUNCTIONS OF GROUT

2.1 General

Grout is injected in the tail void between the soil and the lining. In some cases it is injected through the lining, but most common is a grouting system that is constructed in the backside of the TBM and that can inject grout during drilling continuously, see Figure 1.

Figure 1. Sketch of TBM and detail of injections system.

The grout has different functions, as summarized by Shirlaw et al. (2004):
1. To ensure that there is uniform contact between the lining and the ground: The ground both loads the lining and provides resistance to distortion. Consistent filling of the tail void will avoid uneven loading.
2. To reduce the surface settlement over the tunnel: If the void is not filled with grout, the ground will move into the void, resulting in settlement. Typically, the volume of the tail void is in the range 3% to 16% of the internal volume of the tunnel. There can be high surface settlements if the grouting is ineffective, and the tail void closes as a result.
3. To hold the ring in place during shield advance: Soft ground and mixed face tunnel boring machines...
are typically advanced by thrusting off the installed lining. If the lining is surrounded by liquid grout, then it can float upwards, See Figure 2. This can lead to stepping on the circumferential joint, birds’ mouths developing on the radial joints, loss of plane and damage to the lining.

4. To carry the load transmitted to the lining by the shield back-up trailers.

5. To reduce seepage and loss of fine particles where the gasket is ineffective due to damage or because of stepping of the lining.

In addition to this, grout also has to provide sufficient resistance to overcome the buoyancy forces that occur in the first rings after the TBM. These buoyancy forces occur because the average density of lining and air that forms the tunnel is less than the density of the grout. This is comparable with what is mentioned under 3, but it can be compensated by reduction of the grout density as well as by an increase of the yield stress.

Some of these functions can only be taken into account by the construction of the TBM (sufficient grout injection points) or craftsmanship (taking care for open injection points, consistent filling of the tail void). However, for some it is possible to ‘design’ the grout. In this paper we will discuss the influence of the density, the initial yield stress, the consolidation properties and the hardening of the grout on the loading on the lining. It is focused on forces and moments along the lining. Ring loading is not taken into account.

2.2 Density of the grout and initial viscosity

The density of grout mortars usually varies from 1000 to 2200 kg/m³. The average density of the cross-section of tunnel lining and the air in the tunnel is in general around 400 kg/m³. This means that there will be a buoyancy force on the tunnel. This can lead to upward directed movement of the tunnel lining when it is released from the TBM. Furthermore it induces stresses and moments in the TBM as will be explained later.

The grout mortar can be designed to minimize this buoyancy force by reducing the density and/or decrease the yield strength. The yield strength changes the pressure distribution over the lining. Assuming that the shear strength between the tunnel lining and the grout is small and the shear strength between the soil and the grout determines the pressure distribution, the relation between the yield strength and the maximum buoyancy force that can be compensated by the grout mortar can be written (Bezuijen et al. 2004):

\[ F = \frac{\tau_y D^2}{s} \]  

Where \( F \) is the maximum force per metre tunnel lining that can be compensated by the yield stress in the grout, \( \tau_y \) the shear strength of the grout, \( D \) the diameter of the tunnel and \( s \) the width of the tail void. The buoyancy force \( K \) per metre lining exerted by the tunnel lining can be written as:

\[ K = \frac{\pi}{4} D^2 (\rho_g - \rho_t) g \]  

Where \( \rho_g \) is the density of the grout, \( \rho_t \) the average density of the tunnel (lining and air) and \( g \) the acceleration of gravity.

Equilibrium in a cross-section is reached when \( F \geq K \). Such a situation can be reached when:

\[ \tau_y \geq \frac{\pi}{4} s (\rho_g - \rho_t) g \]  

This relation shows that a stable cross-section can be reached by using grout with high yield strength, a low density or by increasing the average density of the tunnel (and/or dead weight or back-up train).

2.3 Properties along the lining

Although Eq. (3) looks rather simple, it is in a lot of cases not so easy to fulfil this equation directly behind the TBM due to other requirements on the grout mortar. The grout has to flow easily through the piping of the injection system and it has to fill the tail void completely and last but not least also costs play a role. These requirements quite often result in a grout mortar where Eq. (3) is not fulfilled directly after the TBM because the yield stress is too low. When this is the case, a part of lining directly after the TBM will have the tendency to move upward. However, this upward movement will be stopped by the friction forces between the lining elements still in the TBM on
one side and the elements in the already hardened or consolidated grout on the other side. In such a situation it is necessary to know the hardening and consolidation properties of the grout as will be described later.

2.4 Consolidation and hardening

The yield strength of the grout mortar after injection will increase due to consolidation of the grout and hardening. It is of importance to have data to describe this strength increase because this determines over what length the tunnel lining has only limited support. Consolidation can lead to a strength increase for only a limited thickness of the grout layer (Bezuijen & Talmon 2003). This is the case when the tunnel is bored in stiff sand.

3 MEASUREMENTS

This section presents the longitudinal loading on a tunnel lining for 2 projects, the Sophia Rail Tunnel and the Botlek Rail Tunnel, and 3 grout mortars (2 types of grout mortar were used at the Botlek, ‘traditional’ cemented grout and a 2 component grout. Some properties of the grouts used are summarized in Table 1. \( \tau_0 \) is the initial shear stress, just after injection, measured with a vane. For the 2 component grout this value can be even lower just after mixing the 2 components, but this value was measured just after the vane was brought in.

The loading on the lining along the axis of the tunnel can be calculated from grout pressure measurements. The vertical gradient in the grout determines the loading. Assuming a grout pressure along the lining that increases linearly with depth (See Bezuijen et al. 2004), a lining segment will be in equilibrium when:

\[
\frac{dP_g}{dz} = \rho_g g \tag{4}
\]

With \( P_g \) the grout pressure, \( z \) the depth, \( \rho_g \) and \( g \) the acceleration of gravity. The measurements from the Sophia Tunnel, as shown in Figure 3 (Bezuijen et al. 2005), show such an equilibrium at 9 meters from the TBM. In this figure the dots show the measurement points and the line an approximation that will be dealt with later.

Grout pressure measurements performed at the Botlek Rail Tunnel show comparable results, but the measurements were stopped too early to find the equilibrium value. The gradient found at 5 m from the TBM (approximately 5 kPa/m) is close to the equilibrium value, as will be explained later. The average slope of the decrease in the gradient with distance from the TBM is larger than for the Sophia Rail Tunnel (1.75 kPa/m² for the Botlek and 1.14 kPa/m² for Sophia), because of the faster consolidation of the Botlek grout (Bezuijen & Talmon, 2003). This means that the loading on the lining due to the buoyancy forces on the lining is less for the Botlek than for Sophia.

Looking more in detail to the grout pressure gradient as a function of the distance from the TBM, it appears that both tunnels have a remarkable course of this gradient during drilling. Measuring close to the TBM, for example during boring of ring 820 at the Botlek data, there is an increase in the gradient at the end of the boring of that ring (at 1.5 m from the TBM). However, at the boring of ring 821 there is a decrease in the gradient. The most likely explanation for this phenomenon is the lining-grout interaction.

As mentioned before, grout is a Bingham liquid. The yield stress is of importance for the vertical pressure gradient. ‘Fresh’ grout with a low yield stress will be injected during drilling. Furthermore there will be a flow from the TBM into the tail void (Talmon et al. 2003). Both the fresh grout and the flow from the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sophia</th>
<th>‘traditional’</th>
<th>2 comp.</th>
<th>Botlek</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_g ) (kg/m³)</td>
<td>2130</td>
<td>2100</td>
<td>1150</td>
<td></td>
</tr>
<tr>
<td>( \tau_0 ) (kPa)</td>
<td>0.6</td>
<td>0.6</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>vol. loss. (%)</td>
<td>8</td>
<td>10</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>( k ) (m/s)</td>
<td>3e-8</td>
<td>1.5e-7</td>
<td>1e-8</td>
<td></td>
</tr>
</tbody>
</table>

1 Determined from consolidation experiments as described in Bezuijen & Talmon (2003) with 100 kPa confining stress.
2 Estimate, permeability could not be determined accurately.
TBM prevented the build up of a yield stress in vertical direction resulting into a gradient close to the one that corresponds to the hydrostatic pressure distribution for the grout used. This high gradient means that there is a buoyancy force on the tunnel. As drilling stops, yield stress can build up in vertical direction and the pressure gradients decrease.

At a larger distance from the TBM (at 3 m from the TBM for Botlek) consolidation of the grout has resulted in an increase of the yield stress and the grout at that position is no longer influenced by the fresh injected grout. The high buoyancy force closer to the lining will induce some lifting of the lining. At this larger distance however, this lifting is prevented by the stiff grout. The grout more or less pushes the lining downward, which means high pressures on top of the lining and relative low pressures at the bottom and thus a low vertical gradient.

A test section for the first tube and the second tube of the Botlek Rail Tunnel were grouted using 2 component grout (ETAC). Grout pressure measurements are available from the test section. The available data did not include the movement of the TBM but only the status of the machine and the grout pressures as a function of time. From the status it can be seen when there was drilling (status 2) and when not (the other values). The results show large gradients when the instrumented ring leaves the TBM (between 7:00 and 8:00). After 8:00, when the drilling is finished, the gradient immediately settles around 5 kPa/m, indicating that there is a force equilibrium, until approximately 12:00 when the strength of the grout is increased that far that the pressures cannot be measured accurately anymore. The lower density and the fast increase in strength of the grout led to less buoyancy force on the lining and therefore also the boring of the next ring (around 10:00) hardly influences the gradient. This may also be the reason for the high gradients measured at the moment the instrumented lining leaves the TBM. Some movement of the lining in the already strengthened grout may locally lead to high forces and high gradients.

All measurements show that there is only a limited distance where the vertical pressure gradients deviate significantly from the equilibrium condition. This observation was used as a base for the calculation model described in the next section.

4 CALCULATION MODEL

Using the pressure data during drilling, it is possible to construct the load distribution on the tunnel for the part where the lining has the tendency to float. This loading can be used in a numerical program to calculate the shear forces and moments in the lining. The resulting shear forces and moments depend to a large extent on the moments and force exerted by the TBM.

In this paper we focus on the influence of the grout and the influence of consolidation and hardening. We therefore assume a simple calculation model only to get an idea how the loading on the lining is influenced by the buoyancy, the TBM induced moments and consolidation or hardening.

The lining is approximated to a beam that is fixed at the end where the grout is consolidated or hardened. Usually it is assumed that the lining rests on an elastic foundation. However, the measurements, Figure 3, show that forces on the lining are more or less constant at some distance (more than 9 m in the figure) from the TBM. Movement of the lining in the grout would lead to pressure variations in the grout that are not measured. This justifies this approximation.

The other end of the lining bears at the TBM. The TBM can exert a certain moment $M$ on the lining. A loading distribution on the lining is assumed that increases linearly with the distance from where the tunnel lining is fixed in the consolidated grout. This is again only an approximation of the real loading that occurred, see Figure 3 and Figure 4.

It was shown that in all measurements the vertical pressure gradient reaches a value equal to the value that corresponds to the average density of the tunnel. Therefore it can be assumed that at a certain distance from the TBM the shear force on the lining is zero. Using the definition sketch form Figure 6, which was also used for defining the X-axes in Figure 3 and neglecting the influence of the shear forces, the beam equation for this situation can be written as:

$$EI \frac{d^4 y}{dx^4} = -q(x)$$

(5)

Figure 4. Example of gradient in the grout pressure as a function of the distance from the TBM. (X-axes is chosen in a way to allow comparison with Figure 3). Results measured at Botlek Rail Tunnel.
With the boundary conditions:

$$y(0) = 0, \quad \frac{dy(0)}{dx} = 0, \quad \frac{d^3 y(0)}{dx^3} = 0, \quad \frac{d^2 y(L)}{dx^2} = \frac{M}{EI}$$  \hspace{1cm} (6)$$

Where $E$ is Young’s modulus of the lining, $I$ the moment of inertia of the lining, $x = 0$ the position where the grout is hardened, $x = L$ the other end of the lining connected in the TBM, $q$ the increase of the loading with distance $x$ and $M$ the moment the TBM exerted on the lining. The second boundary condition implies that the shear force $F_s(0) = 0$. For these boundary conditions the movement of the lining can be written as:

$$y(x) = -\frac{x^2}{120EI} \left( q x^3 - 10q L^3 - 60M \right)$$  \hspace{1cm} (7)$$

and the shear force ($F_s$) as:

$$F_s(x) = 0.5q x^2$$  \hspace{1cm} (8)$$

With a length of the liquid zone of approximately 9 m and a tunnel with a diameter of 10 m, a beam equation cannot be more than an approximation, but as said before that is enough to get an idea of the importance of various parameters.

When the position of the tunnel is measured as is shown in Figure 2, it is also possible to solve the differential equation for a fixed displacement (Bezuijen et al. 2005).

5 EXAMPLE CALCULATIONS

5.1 Sophia Rail Tunnel

As example the measurements for the Sophia Rail Tunnel are used. The measured pressure gradients are already shown in Figure 3. In this figure the pressure gradient during drilling is most prominent; because then the TBM is moving and $x$ is changing (the pressures were measured in one ring of the lining). The vertical points in the plot show the change in gradient during stand still. The constant value of 6.9 kPa/m is higher than the value that corresponds to the weight of the tunnel (4 kPa/m) but will also be influenced by weight of equipment in the lining. The value of $q$ can be determined from $a$ in Figure 3:

$$q = aO$$  \hspace{1cm} (9)$$

With $O$ the cross-sectional area of the tunnel lining. $q$ is 80 kN/m$^2$ for a tunnel with a diameter of 9.45 m as the Sophia Rail Tunnel.

The momentum on the tunnel lining for the Sophia Rail Tunnel as given in Bezuijen et al. (2004) is shown in Figure 7. Momentum is approximately 10 MNm during stand still and 18 MNm during drilling.

The stiffness of the lining is not well known. We used Eq. (7) and the measured displacement (Figure 2) to determine the stiffness. By adjusting the stiffness of the lining to $EI = 5.4 \times 10^7$ kNm$^2$ the measured displacement at $x = L$ was found. Results of this calculation are shown in Figure 8 and Table 2.

The course of the calculated vertical displacement is also compared with the measured displacement in Figure 2 and showed reasonable agreement. This result means that the effective stiffness of the lining in liquid grout is less than normally assumed. It is possible that the segmented lining has more degrees of freedom than is assumed traditionally. It further implies that there is a considerable shear force present at the TBM that is counterbalanced by the weight of the TBM and the lining elements in the TBM. In this example a measured $q$ was used, but this $q$ is not the result from the grout.
Table 2. Parameters and results of beam calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sophia</th>
<th>Botlek</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L$ (length of ‘unsupported’ zone)</td>
<td>9</td>
<td>5</td>
<td>m</td>
</tr>
<tr>
<td>$q$ (distributed loading near TBM)</td>
<td>80</td>
<td>123</td>
<td>kN/m$^2$</td>
</tr>
<tr>
<td>$EI$ (stiffness of lining)</td>
<td>$5.4 \times 10^7$</td>
<td>$5.4 \times 10^7$</td>
<td>kNm$^2$</td>
</tr>
<tr>
<td>$M$ (moment on TBM)</td>
<td>18</td>
<td>22</td>
<td>MNm</td>
</tr>
<tr>
<td><strong>Result</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A$ (displacement of lining)</td>
<td>0.02</td>
<td>0.0056</td>
<td>m</td>
</tr>
<tr>
<td>$M$ ($x = 0$)</td>
<td>28</td>
<td>24.6</td>
<td>MNm</td>
</tr>
<tr>
<td>$F_{s,TBM}$ (shear force at $x = L$)</td>
<td>3.2</td>
<td>1.5</td>
<td>MN</td>
</tr>
</tbody>
</table>

Figure 7. Sophia Rail tunnel. Momentum in vertical direction that is exerted on the lining by the plungers in the TBM. A positive momentum means that the forces on the lower part of the tunnel are higher than on the upper part.

Figure 8. Results of calculation model. Calculated moments are divided by 10.

properties only. For a situation with zero shear force $F_s$ at $x = 0$, the values of the parameters in Eq. (5) also determine $q$ so that $F_s = 0$ for $x = 0$, or to say it differently: not always all possible shear stress in the grout is mobilized.

Consequence is that the influence of $L$ (the length with linearly increasing grout pressure gradient) cannot be found by simply increasing $L$ in Eq. (4). Assuming that the pressure gradient in the grout remains the same, it is also necessary to change $q$ (the faster consolidating grout, Figure 4, of the Botlek led to a different value of $a$, in Eq. (8), compared to the Sophia Rail Tunnel.

Measurements for the Botlek Rail way were also used. However, data on the vertical displacement of the lining are not available for this case. It is therefore assumed that the stiffness of the lining is the same in both the Botlek and the Sophia Rail Tunnel. This is a reasonable assumption, since both linings are comparable. The moment on the TBM was a bit higher around 20 MNm. $q$ as determined from $a$ was 123 kN/m$^2$ and $L$ is assumed to be 5 m. The results of this calculation are also shown in Table 2.

The results show clearly that the faster consolidation of the grout leads to smaller displacements, moments and shear force at $x = L$. However, it should be noted that this result is obtained because the shear stress of the fresh grout is assumed to be small. A higher starting viscosity of the grout also leads to lower displacements, moments and shear forces (Bezuijen et al. 2005)

5.2 Two component grout

The available measurements for the 2 component grout are too incomplete to make a calculation as presented in Table 3. What can be done is check some variations. In one variation it is assumed that the length $L$ is only one tunnel ring. The continuum calculation model described above, assuming elastic beams, will not produce accurate values, but it will show the influence of such a short value of $L$. Another calculation shows the result for the situation that 2 rings are necessary to get equilibrium. Although this last calculation leads to a considerable larger vertical movement, than the first one, the movement is still in the millimeters.

Other calculation examples are presented in Bezuijen et al. (2005).

6 CONCLUSIONS

The work described in the paper has led to the following conclusions:

– A minimum grout strength is necessary for an equilibrium condition of the lining.
– The length of the insufficient supported zone is of crucial influence on the movement of the tunnel, the shear force at the TBM and the moments in the lining. Movements and moments can be reduced by reducing the length of this zone by changing the hardening or consolidation properties of the grout. Yield strength and density of the grout also influences the longitudinal loading on the lining.
Table 3. Calculations for 2 component grout, see also text.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2 comp calc 1</th>
<th>2 comp calc 2</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>( L ) (length of 'unsupported' zone)</td>
<td>1.5</td>
<td>3</td>
<td>m</td>
</tr>
<tr>
<td>( q ) (distributed loading near TBM)</td>
<td>1613</td>
<td>807</td>
<td>kN/m²</td>
</tr>
<tr>
<td>( EI ) (stiffness of lining)</td>
<td>(5.4*10^7)</td>
<td>(5.4*10^7)</td>
<td>KNm²</td>
</tr>
<tr>
<td>( M ) (moment on TBM)</td>
<td>22</td>
<td>22</td>
<td>MNm</td>
</tr>
<tr>
<td>Result</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( A ) (displacement of lining)</td>
<td>0.0005</td>
<td>0.002</td>
<td>m</td>
</tr>
<tr>
<td>( M ) (( x = 0 ))</td>
<td>23</td>
<td>25</td>
<td>MNm</td>
</tr>
<tr>
<td>( F_{s,TBM} ) (shear force at ( x = L ))</td>
<td>1.8</td>
<td>3.6</td>
<td>MN</td>
</tr>
</tbody>
</table>

– A short unsupported zone and some forced movements of the lining, induced by the TBM movements, can locally lead to considerable loading on the lining. The influence on the longitudinal loading as calculated in this paper is still limited, but a considerable ring loading can be expected.

– The model presented shows quantitatively the influence of changing the grout parameters on the loading on the lining.

REFERENCES


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