In this article, Dr Benoît Jones, Director of the Tunnelling and Underground Space MSc at the University of Warwick, UK, looks at recent developments in the design of segmental lining joints, focussing on jacking forces, grout pressures and longitudinal effects.

Segmental linings – longitudinal effects

THERE HAVE BEEN SIGNIFICANT ADVANCES in our understanding of segmental lining behaviour in the last 15 years from instrumented rings in actual tunnels, full scale or reduced scale laboratory tests and 3D numerical modelling. This article will attempt to summarise this work, with particular focus on the effect of jacking forces, grout pressures and longitudinal effects.

As mentioned in my previous article, virtually all the cracking and damage to segmental linings occurs during ringbuilding, jacking the TBM forward and grouting. This is evidence that these processes induce significant stresses and deformations in the lining. However, these are usually ignored and usually an ideal situation is assumed as the initial condition for conventional calculation, which is probably not realistic (Bakker & Bezuijen, 2009; Bilotta & Russo, 2012).

Introduction

In my previous article, I listed the following factors that are ignored or dealt with in a simplistic way by conventional calculation, i.e. bedded beam models and analytical solutions (Blom et al., 1999; Molins & Arnau, 2011):

- Staggering of joints in adjacent rings
- Packing material in the joints
- Grout pressure and grout hardening
- The type of joints and their rotational stiffness
- Redistribution of moments via shear stress across the circumferential joint to adjacent rings
- The effect of longitudinal compression in the tunnel caused by the TBM jacks
- Restraint from the shield, and in particular the tailseal brushes
- What happens when radial joints are not parallel to the axis of the tunnel, e.g. when trapezoidal or hexagonal segments are used.

In the previous issue of Tunnelling Journal we discussed staggered radial joints, packers, joint geometry, rotation and misalignment of joints. In this issue we will talk about jacking forces, grout pressures and longitudinal effects.

Jacking forces

Burgers et al. (2007) used 3D numerical modelling to investigate the effect of jacking forces on steel fibre reinforced segments for the Barcelona Line 9 tunnels. Each ring consisted of 7 segments plus a key segment, the tunnel was about 12m diameter and each segment had an arc length of 4.70m. Each segment was loaded by two pairs of thrust rams. The trailing edge of each segment had 4 bearing pads to help transfer jacking loads to the previous ring. As jacking loads were increased, the first cracks were formed between the loading surfaces (the ram shoes) due to spalling. At higher loads, splitting cracks developed under the loading surfaces. The steel fibres ensured that cracks propagated in a controlled manner and increased load resulted in more cracks rather than widening of a single crack.

This numerical model ignored the effect of imperfections in the segments or geometrical tolerances in ring assembly. The ring joint may not be plane and the jacking forces may not be applied perfectly. Therefore, Burgers et al. (2007) went on to analyse the effects of eccentric placement of a thrust jack in the radial direction by applying the force with a triangular pressure distribution. This caused a significant reduction in the failure load from 30.7MN to 23.6MN and cracking began much earlier in the test. The (exaggerated) deformation of a segment due to eccentricity of the jacking load towards the extrados of the circumferential joint is shown in Figure 1. It causes a bending moment about a tangential axis on the left, and a bending moment about a radial axis on the right, which would cause a longitudinal tensile crack on the leading edge of the segment between the two pairs of jacks, due to the uneven support on the trailing edge. Cracks exactly like this one were observed during construction of Line 9.

Another possible cause of longitudinal cracks between the ram shoes is uneven support due to steps in the circumferential joint plane (de Waal, 1999). Cavalaro et al. (2011) say that this is the most common cause of this type of cracking. A diagram from their paper is shown in Figure 2.

The effect of this uneven support depends on its magnitude, on the thickness and

Figure 1: Bending moments induced by eccentricity of jacking load towards the extrados (from Burgers et al., 2007).

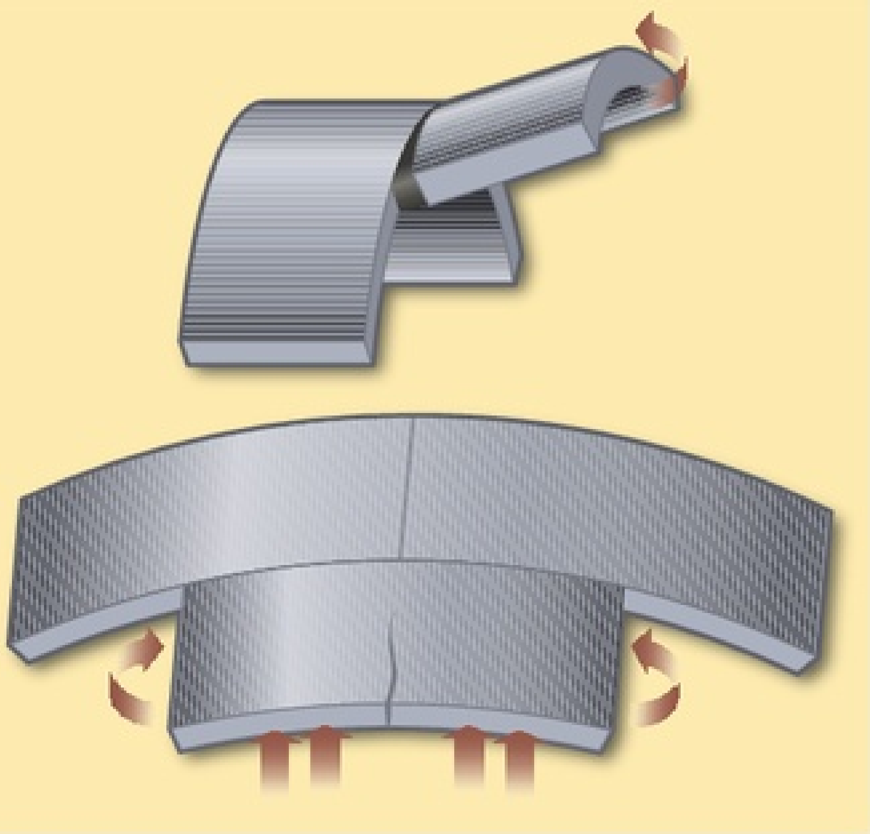
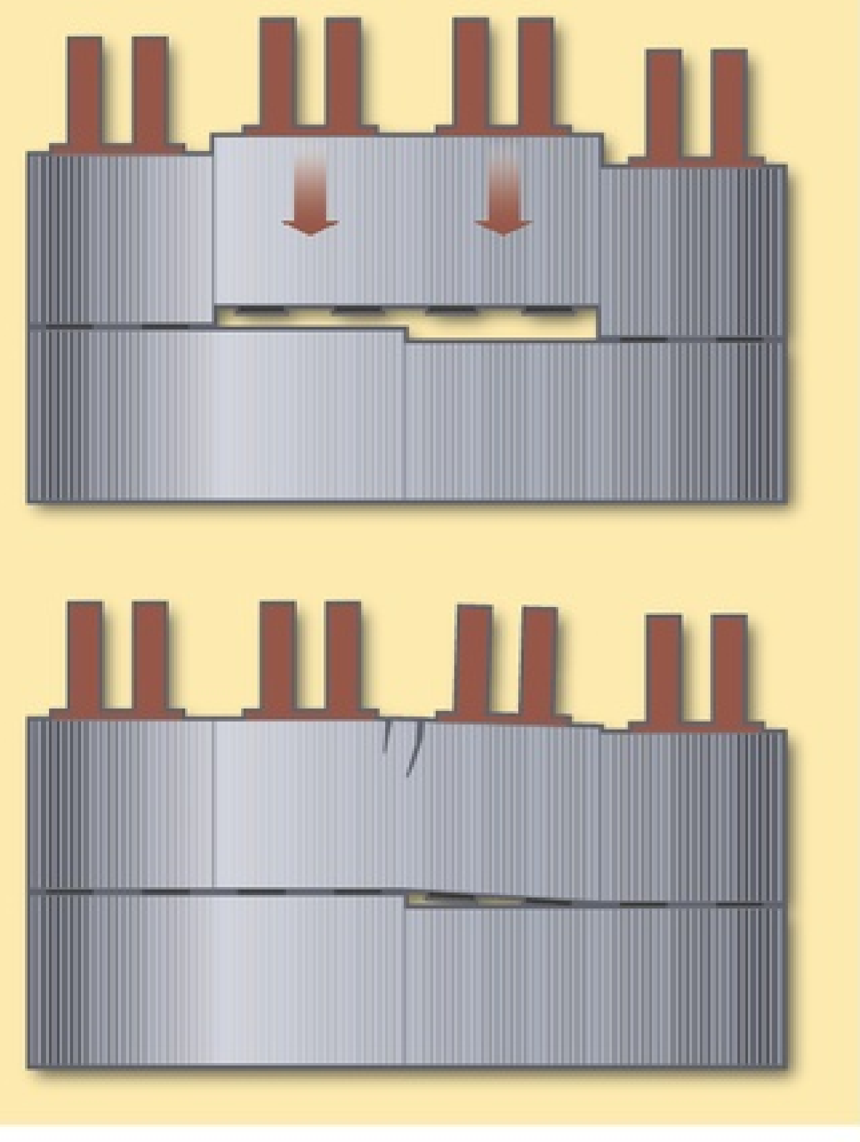


Figure 2: Longitudinal cracks caused by uneven support (from Cavalaro et al., 2011).



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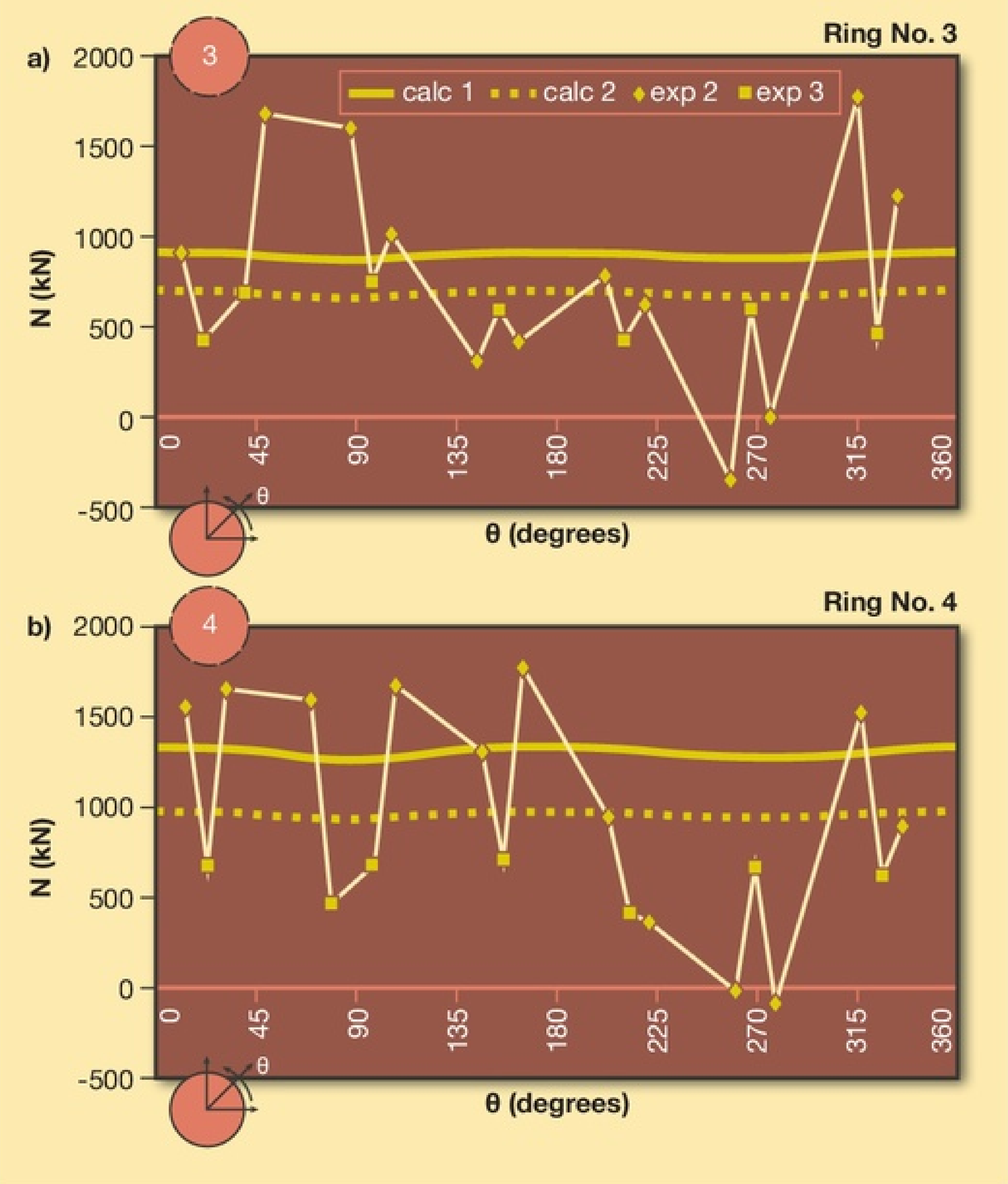
material properties of the segments, and on the thickness and material properties of the packing material. For a small step between segments in the previous ring, the new segment will deform until contact is made across the gap, with only a small reduction in capacity. For a larger step critical damage may occur before contact is made. Cavalaro et al. (2011) found that thinner and wider (in longitudinal direction) rings could cope with larger steps. Thinner linings have a lower stiffness, allowing more deformation to occur to close the gap before critical stresses are induced. Wider rings, although stiffer, allow more load to be transferred to the first contact and therefore result in lower tensile stresses between the ram shoes. A lower packer stiffness was found to help too. Heijmans & Jansen (1999) looked at this load case for the design of the Pannerdensch Kanaal Tunnel and found that the gap needed to be less than a few tenths of a millimetre to avoid cracking.

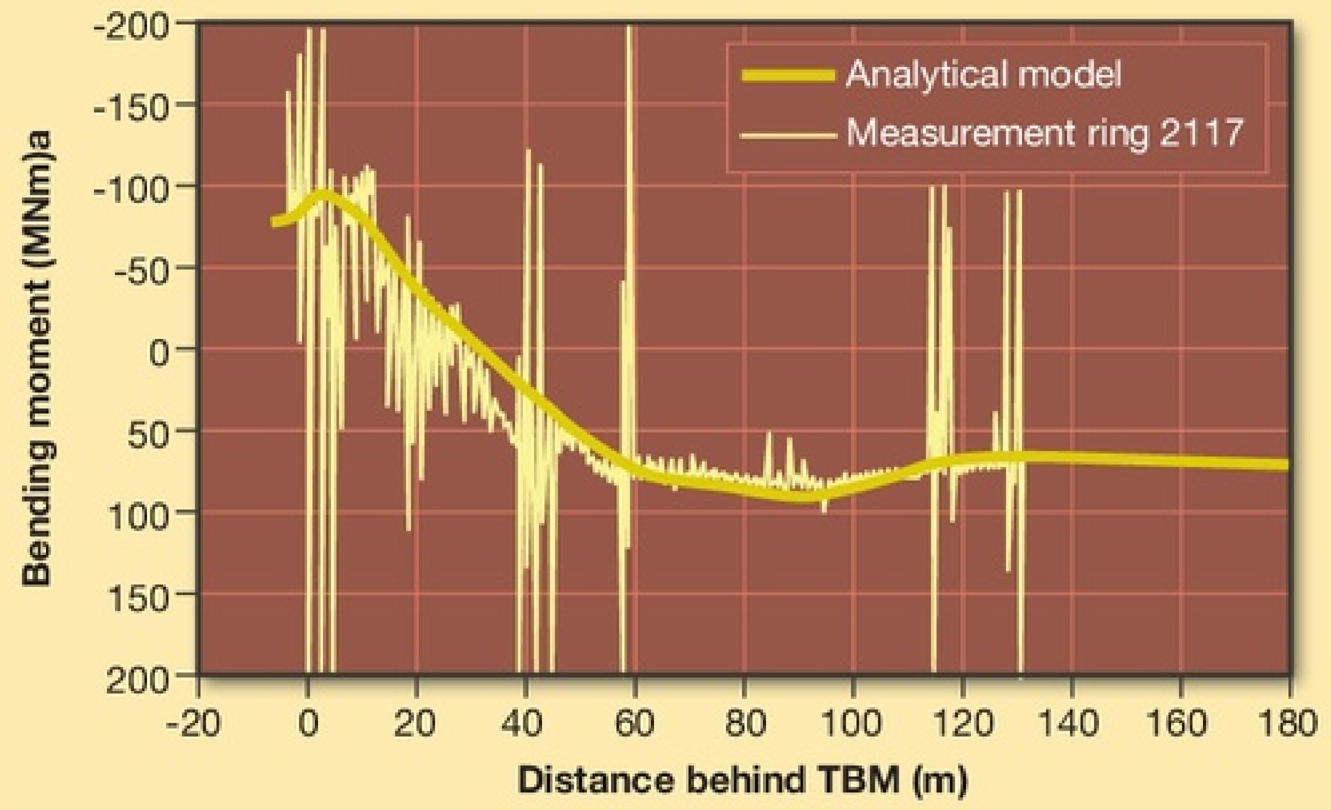
Bilotta & Russo (2012) installed strain gauges in segments used for the Line 1 tunnels in Naples. They found that the jacking forces caused a high longitudinal compression, as one would expect, but also an extension in the circumferential direction, which they attributed to a Poisson's ratio effect and the lack of significant restraint to the ring within the tailskin. This circumferential extension was later reversed by grouting and ground load.

Figure 3: Hoop forces around (a) ring no.3 and (b) ring no.4. 'exp 3' points are at the joints and 'exp 2' points are within the body of the segments, 'calc 1' and 'calc 2' are analytical solutions (from Bilotta & Russo, 2012).



By using a back-calculation method, Bilotta & Russo (2012) also calculated internal forces around the lining. The assembly of the lining, jacking forces and grout pressures resulted in a highly variable hoop axial force and bending moment distribution, particularly if the longitudinal strains were taken into account in the calculation, as shown in Figure 3. Hoop axial forces were lower at joints than in the body of the segment. Bilotta & Russo explained that the segments were placed quite smoothly, but didn't explain where the hoop force was going. It is possible that the hoop force could have been transferred via dowels and friction in the circumferential joints to the adjacent segments rather than across the joints.

Figure 4: Strain gauge data and analytical model of the Groene Hart Tunnel (from Hoefsloot, 2009).



If the results of Bilotta & Russo's back-calculation are taken at face value, the most interesting aspect is how much real hoop thrusts vary within segments and around the ring compared to conventional calculations using analytical solutions. The effects of small geometric misalignments, asperities, variable and/or eccentric jacking forces and grout pressures in the real situation clearly have a big impact on the forces in the segments in the medium to long-term.

Longitudinal effects

Hoefsloot (2009) used an analytical model and also strain gauge measurements from the Groene Hart Tunnel to show that jacking forces remain in the tunnel lining permanently. At a distance of about 40m behind the TBM, average longitudinal axial force in the lining had decreased to approximately 70% of the jacking load, and this stayed in the lining permanently. Talmon et al. (2009), in an accompanying paper, calculated that the residual axial force acted at 1.5m above the axis level of the Groene Hart Tunnel, meaning a significant residual longitudinal bending moment is also left in the tunnel permanently.

Figure 4, taken from Hoefsloot (2009) shows that longitudinal bending moments (about the axis or springline of the tunnel) are also generated due to jacking loads. These bending moments are caused by the fact that jacking forces tend to be higher at the invert to counteract the tendency for TBMs to dive, perhaps due to the weight of the cutterhead and higher friction around the bottom part of the shield. The rings within the TBM are also to some extent cantilevering off the rings further back where the grout has hardened (Hoefsloot & Verweij, 2006). With distance behind the TBM, these bending moments are gradually reversed by grout pressures and the weight of the backup equipment.

Predicting these longitudinal bending moments is complex, but can be done analytically or numerically, as shown by Hoefsloot (2009), Hoefsloot & Verweij (2006) and Talmon et al. (2009). They depend mainly on the distribution of jacking forces, restraint provided by the shield/tailseal brushes, the properties of the grout, and the position and weight of the backup.

Hoefsloot (2009) also found that the bending moment distribution in Figure 4 also means that the last ring built nearly always has overhang. The new ring has to be placed to the design alignment, hence there will always be a change in plane of the rings and perhaps stepping. This can cause eccentric loads to be applied across the circumferential joint and increases the risk of cracking. Another problem is that the TBM itself often has lookup while the rings in the tailskin have overhang, which results in wear to the tailseal brushes or excessive forces applied to the segments, similar to what happens on a tight curve.

The effect of ringbuilding tolerances, stiffness of tailseal brushes and TBM attitude were investigated in detail by Mo & Chen (2008) using a 3D numerical model. They found that the key segment was the most vulnerable to dislocation or overstressing and this meant that the TBM diving downwards was the worst case.

As anyone who has bent a pipe will know, tubes flatten in bending, and so the longitudinal bending of the tunnel would also cause it to squat, as shown by Huang et al. (2012).

Koyama (2003) used pressure cells on the extrados of segments to measure the pressure applied by the tailseal brushes and found that it could be twice as high as the pressure later exerted by the ground. Also, he found that tight curves could result in permanent loads and deformations in the lining.

Grout pressures and tailseal brushes

Initially, when grout is pumped into the tail void, the principal direction of flow is circumferential (Talmon et al. (2006). Further back from the injection point, the velocity is slower and the grout flow is longitudinal. By modelling the flow using a Bingham model for the grout based on laboratory tests, Talmon et al. found that the grout pressures exerted on the tunnel lining depended on the grout ports used. When all 6 grout ports were used uniformly (Figure 5), the pressure distribution increased linearly with depth, whereas when only the top 3 grout ports were used, the downwards flow made the pressure distribution approximately uniform (Figure 6). Talmon et al. (2009) later showed that the 'centre of gravity' of the grout injection relative to the axis of the tunnel could be used to calculate the uplift force for situations between these two limiting cases.

Figure 5: Calculated grout pressures at 0m and 4.1m from rear of TBM using 6 injection ports uniformly (from Talmon et al., 2006).

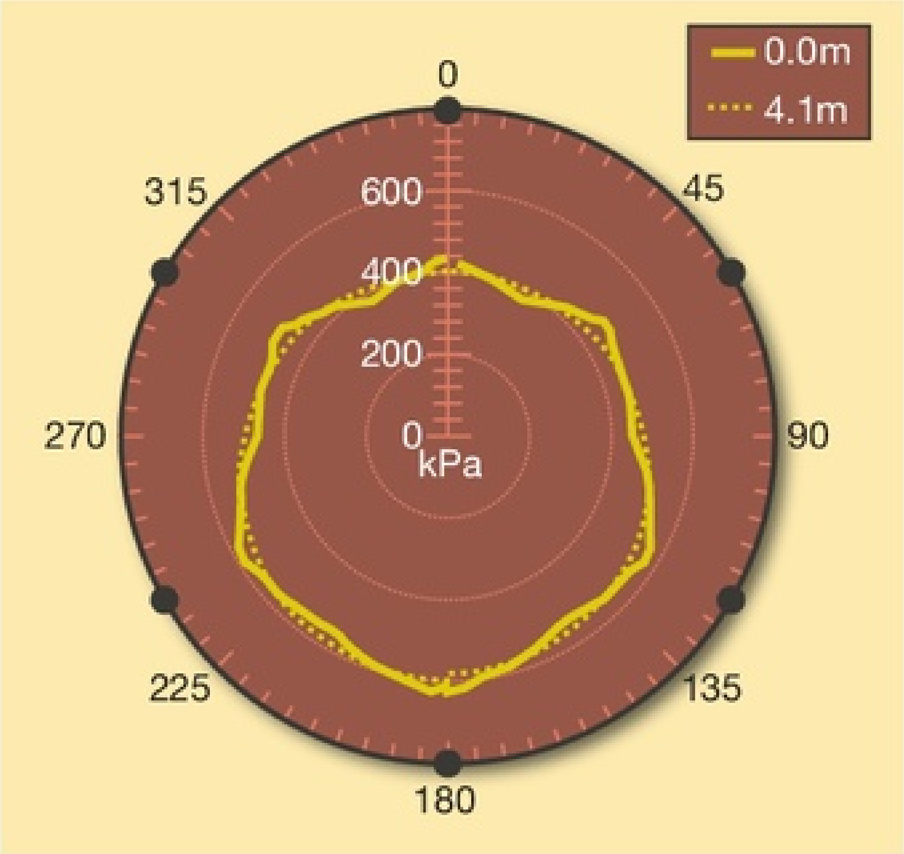
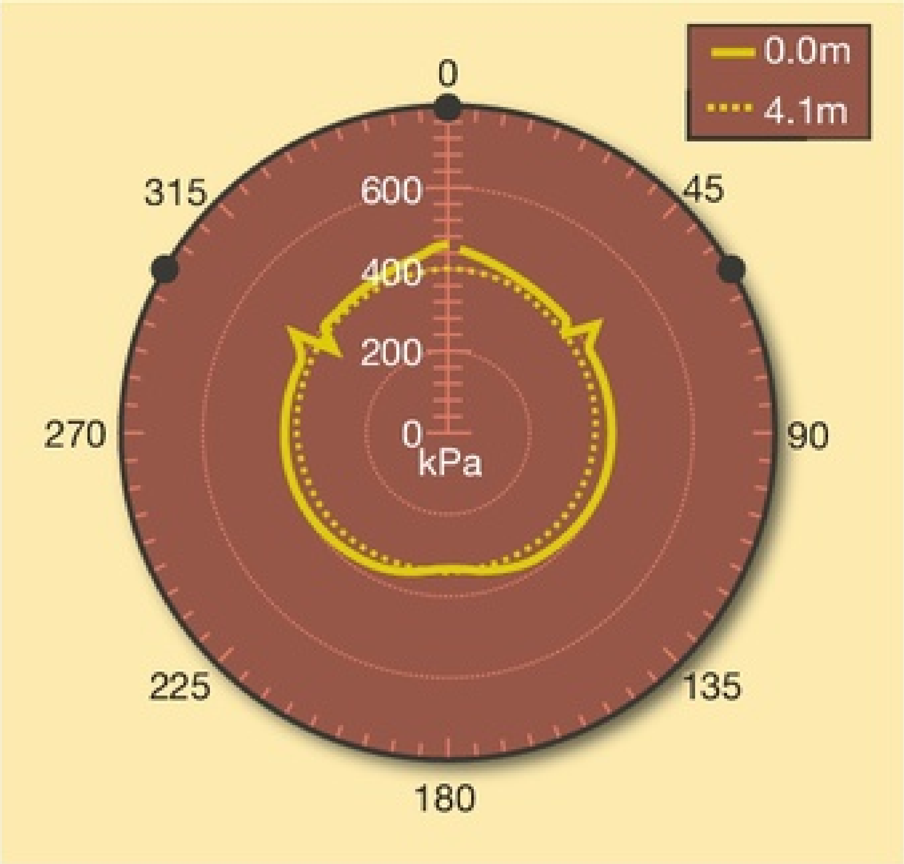


Figure 6: Calculated grout pressures at 0m and 4.1m from rear of TBM using top 3 injection ports only (from Talmon et al., 2006).



The linear increase of grout pressure with depth in Figure 5 is not hydrostatic, but increases at a lower rate than the unit weight of the grout. This is due to buoyancy of the tunnel lining, which applies an uplift force on the grout. By taking this into account, Talmon et al. (2006) found good agreement with field measurements of grout pressure.

If the grout exerts an uplift force on the tunnel lining, then this is resisted by the rings within the TBM, and by the rings further back where the grout has hardened (Hoefsloot & Verweij, 2006). It is also resisted by the self-weight of the rings and the weight of the TBM backup and depends on the properties of the grout. The effect is obviously worse if inert or unaccelerated grouts are used rather than grouts with faster setting times. The tunnel is therefore like a pipe supported at both ends with an upwards pressure in the middle. This induces longitudinal bending moments in the tunnel, which can exacerbate the deformations due to jacking loads. A basic conclusion from this Dutch research is that by injecting more grout through the upper injection ports, uplift forces on the lining, and hence longitudinal bending moments, can be reduced.

Conclusions

There is a complex interaction between the TBM, the segmental lining and the grout, which results in transient and permanent stresses and deformations. Conventional design methods usually only capture these effects partially and in isolation.

As well as the segmental lining material properties, geometry and tolerances, it seems that detailed knowledge of the TBM is required in order to properly design a segmental tunnel lining and this may include:

- Precise geometry of the TBM jacks, their shoes, the tailskin and the tailseal brushes.
- The location of grout ports, the grout rheology and hardening parameters, and grouting strategy (i.e. how much to inject through each port).
- Likely range of advance rates.
- Jacking forces and their potential eccentricity.

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