Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-1-7

QUANTIFICATION OF INSTALLATION INACCURACIES AND THEIR EFFECT ON THE DESIGN OF SEGMENTAL TUNNEL LININGS

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The design of segmental tunnel linings requires a clear identification of loads during construction. Displacement monitoring of the Liefkenshoek tunnel in Belgium has shown important deformations occur in the first week after installation. Afterwards no significant deformations are measured. The manually-operated segment installation causes significant imperfections in joints between segments. These remain present during the lifetime of the structure, permanently disrupting the natural force transfer between individual tunnel segments. The joint irregularities obtained from ovalization measurements were used as input in an FE-model. Calculations showed that the resulting deformations do not correspond to the classical predictions. The installation imperfections cause a transfer of normal forces to the neighboring rings via friction in the ring joints. At the same time the bending moments show a distinctive disturbance in respect to the perfect tunnel ring. These results prove that the effect of installation imperfections should not be neglected in the design of segmental tunnel linings.

Keywords: Shield tunneling, Precast segments, FE-analysis, Ovalization monitoring.

1 INTRODUCTION

Mechanized tunneling techniques such as closed-shield tunneling form an important part of the underground construction industry. Their application often implies the use of segmental tunnel linings as primary or only load-bearing component. Defining loads on a tunnel lining is one of the most challenging aspects of an underground project. Naturally, shield-driven tunnels are designed with respect to soil and groundwater pressures acting along the tunnel profile, together with possible overburden loads on the surface level. However, other load conditions occur during and after construction that have to be taken into account in the design of the tunnel lining, in order to ensure the long-term durability of the underground structure (Schotte *et al.* 2014).

Due to the complex nature of the mechanized tunneling procedure, shield tunneling requires special attention to the loads during construction of the segmental lining. For instance, the assembly of the individual precast segments into a tunnel ring is still done using a manually-operated erector, prone to human error. Therefore small deviations of the theoretical tunnel profile are an inevitable part of segmental lining construction. The question is how these imperfections influence stress behavior in concrete lining. In this respect, various techniques of structural monitoring allow verification of design assumptions by monitoring the real-time behavior of the tunnel lining. During recent construction of the Liefkenshoek rail tunnel in the Port of Antwerp (Belgium), in-situ deformations of the tunnel lining were monitored using laser scanning in a number of cross-sections. The results immediately after assembly of a tunnel ring quantify the inaccurate placement of the segments, which was used as input for a numerical verification model using Finite Element (FE) modeling. The FE-model aims to assess the impact of the installation inaccuracies on the sectional forces.

2 LIEFKENSHOEK RAIL LINK PROJECT

The Liefkenshoek project recently established a new railway connection for freight traffic between the banks of the River Scheldt in Antwerp. This new rail link has a total length of approximately 16 km, of which six km was constructed as a twin-bored tunnel using the mix-shield method. Both parallel single-track tunnels have an internal diameter of 7.30 m. Each tunnel ring is 1.80 m wide and consists of seven concrete segments and a smaller keystone, all of 0.40 m thickness in C50/60 concrete quality (Boxheimer and Mignon 2009). The structure crosses the River Scheldt and the Port Canal with a shallow soil cover (three to ten meters). The tunnel alignment is mainly located in tertiary sands, although at its deepest point below the River Scheldt, the Boom clay ranges up to almost 40% of the tunnel cross-section. An overview of the tunnel alignment and the soil characteristics can be seen in Figure 1.

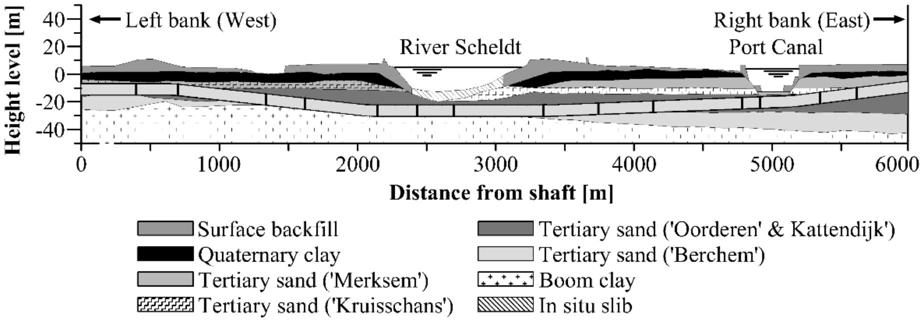

Figure 1. Longitudinal profile of the Liefkenshoek rail tunnel with soil characteristics.

3 OVALIZATION MONITORING

Ovalization was measured using laser scanning at 14 cross-sections in each tunnel tube. Locations of measurement sections along the tunnel alignment are shown in Figure 1.

3.1 Monitoring Procedure

During construction, the deformations of the tunnel lining were monitored at the 14 cross-sections using a Leica HDS6100 laser scanner. Following the methodology described in Nuttens (2014), an experimental standard deviation of 0.44 mm in actual tunnel conditions was established. Seven moments in time were defined at which the selected tunnel sections were measured: the "critical" measurement immediately after construction of the tunnel section, a measurement every week during the first month after installation, and measurements two and three months after installation. Due to limited space in the head of the TBM, three scanning positions covered the whole tunnel section during a critical measurement. Control measurements required only one scanning position, where the laser scanner was mounted on a tripod in the bottom center of the tunnel section. Then the obtained point cloud was manually filtered for clear visualization of the cross-sectional deformations of the corresponding tunnel section.

3.2 Global Results of Ovalization Measurements

The ovalization results show a substantial variation in the deformation pattern for the various tunnel sections. This is due to the distribution of the monitored locations along the tunnel trajectory. Every section acts in response to the corresponding local surroundings, which often influence various parameters of the shield tunneling process as well. Nonetheless, conclusions can be drawn from the combined ovalization results.

Due to the manually-operated installation of the segments, a tunnel ring is never perfectly circular. The left side of Figure 2 shows that on average, the installed ring profile is “egg-shaped”: i.e., the vertical ring diameter is larger than the horizontal diameter and the design tunnel diameter. After interaction with the tail-grouting pressures and soil and water loads, a diverse deformation pattern can be identified for the monitored sections, depending on their location along the tunnel alignment.

However, the global average deformation obtained by the first control measurements (CM) one week after installation shows a horizontal ovalization of the tunnel rings, as seen in the left diagram of Figure 2. The horizontal tunnel diameter exceeds the vertical diameter, complying with classical expectations for circular tunnels in soft ground. The consequential deformations between ring erection and the first control measurement correspond with these observations, as seen on the right side of Figure 2. The top and invert show an average inward displacement of 5 mm, which is larger than the deformation on the sides.

Finally, Figure 2 also shows the deformations measured between the first and last control measurement about three months later. Basically no significant deformations occur after the first control measurement, as the variation of the tunnel radius stays well within the 95% confidence intervals (CI) of the measurements. Therefore it can be concluded that all notable deformations of the tunnel lining occur during the first week after installation. Probably they largely occur in the short period following the exit of the tunnel ring out of the tail shield. However, due to the equipment of the tunnel-boring machine (TBM) blocking the line of sight at this time, no additional ovalization measurements could be performed to verify this presumption.

3.3 Joint Behavior

Apart from the global deformation pattern of the tunnel sections, the ovalization measurement gives insight into the behavior of the joints between adjacent lining segments. Due to inaccurate installation, small irregularities of the inner tunnel surface are present at the location of the joints. In general, these initial joint dislocations range from around 2.5 mm on average to a maximum of about 6 mm. In the period between installation and the first control measurement, the segment joints show the largest displacements, as seen in Figure 3. After CM 1, no significant displacements occur in the joint, parallel to the conclusions of the general cross-sectional deformations. However, the average magnitude of the joint dislocations remains virtually constant over the three months between installation and the last CM.

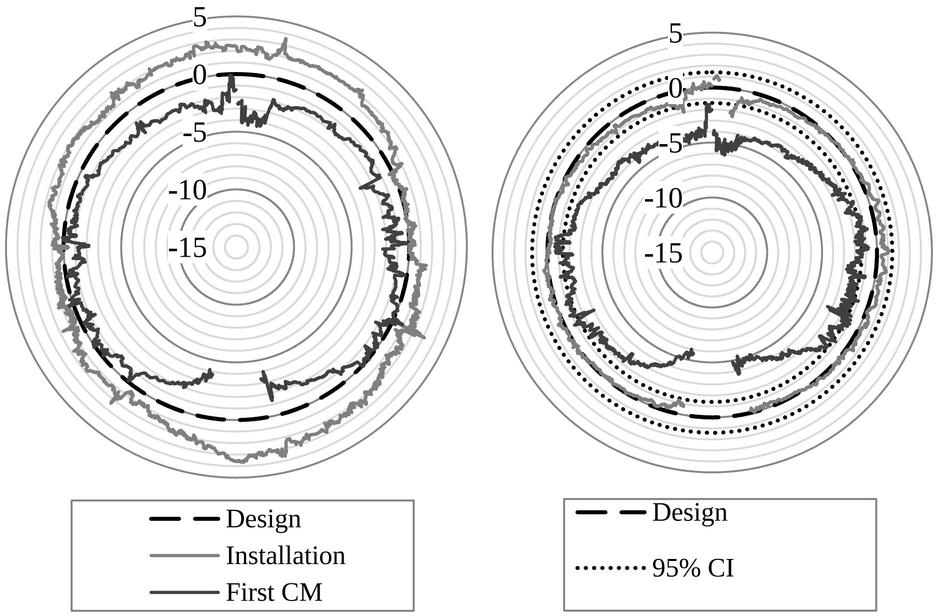

Figure 2. Left: Average deviation (mm) of inner tunnel radius with respect to design radius. Right: Average variation (mm) of inner tunnel radius between measurements.

Similar to joint behavior, the angular orientation of segments relative to the design orientation changes most in the week after installation. Again, this has a negligible effect on the overall magnitude of angular deviation from the design. After the initial week, almost no significant segment rotations are detected between subsequent measurements. Therefore, Figure 3 confirms the findings of the previous paragraph, i.e., all notable lining deformations occur during the first week after erection. However, Figure 3 also leads to the observation that the initial joint inaccuracies present after installation of the segments remain visible in the remaining lifetime of the structure. Their order of magnitude is not reduced after the soil and water pressures act upon the tunnel lining. Therefore it is not unlikely that the joint dislocations have an influence on the deformation behavior and stress distribution in the concrete segments. To investigate this effect further, FE-modeling was applied.

4 FINITE ELEMENT MODELING

Using the results of the ovalization monitoring, two tunnel sections were selected that showed the most interesting results regarding joint behavior and overall deformations. One of these sections was modeled using finite element software; see Figure 4 (right). Three adjacent tunnel rings were modeled using the exact geometry and configuration of individual segments of the Liefkenshoek Tunnel. The ground support was modeled using soil springs with a stiffness according to Duddeck (1980). Thrust forces were applied at the TBM-side of the model, and adequate boundary conditions were modeled at the other end to simulate the presence of the earlier installed tunnel sections. Instead of modeling the joints between the segments as rotation springs, which is most common in the literature, they were modeled using contact conditions with friction.

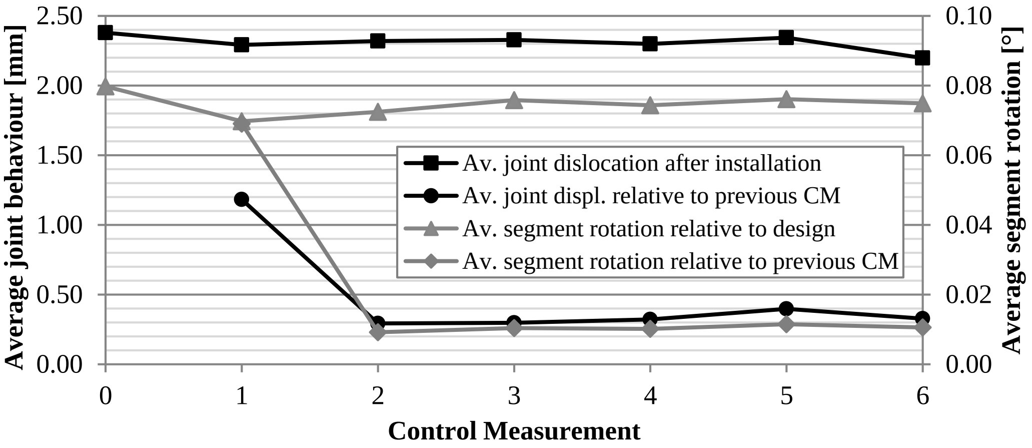

Figure 3. Average joint irregularity and segment rotation for consecutive measurements.

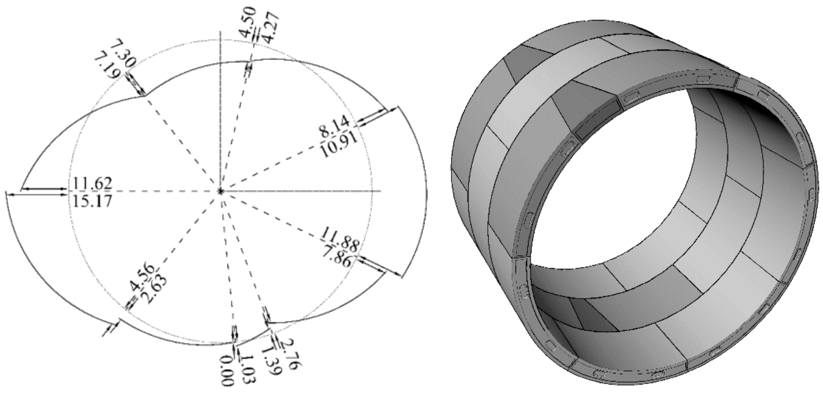

Figure 4. Left: Modeled installation inaccuracies in mm (100x enlarged). Right: FE-model.

Two separate models were developed: one using perfectly circular tunnel sections according to the design, and a second one where the middle ring was modeled with installation inaccuracies. For the latter, the results of the ovalization measurement immediately after installation were used as input for the joint irregularities and segment orientations in the FE-software. Figure 4 (left) shows the applied joint dislocations in millimeters (100 times enlarged) for the central tunnel ring of the second model.

Both FE-models were calculated using the soil and water pressures according to the corresponding location of the section in the tunnel project. The results showed a strong distinction between the models with or without installation inaccuracies. The displacements of the second model clearly differed from the classical deformation pattern of the perfectly circular rings in the first model. The joint irregularities also caused a strong reduction of about 30-50% of the normal forces in the middle ring, as shown in Figure 5 (left). Due to the imperfect contact in the segment joints, the forces are transferred to the neighboring rings via friction in the ring joints. Consequently, the normal force in both adjacent rings, perfectly circular in the FE-model, increases about half of the amount of the reduction in the middle ring. Despite the decrease in normal forces, the curves of the bending moments were relatively similar in both models. Nevertheless the joint dislocations caused some distinctive disturbance in respect to the perfect tunnel ring.

5 CONCLUSION

Due to the manually operated segment installation, significant joint imperfections are present in segmental tunnel linings. As the joint irregularities remain visible during the lifetime of the structure, they permanently disrupt the natural force transfer between individual tunnel segments. Resulting deformations do not correspond to the classical predictions. Naturally, this effect influences the behavior of the segmental tunnel lining and shows that the installation effects should not be neglected in the structural design.

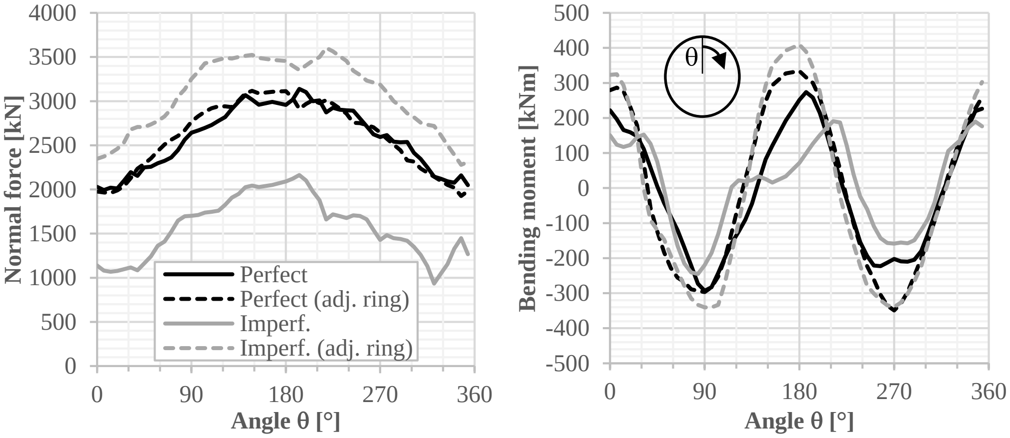

Figure 5. Comparison of calculated normal forces (left) and bending moments (right).

References

Boxheimer, S. and Mignon, J., Liefkenshoek Railway Tunnel in Antwerp, *Tunnel*, 2009(07), 25-31, July, 2009.

Duddeck, H., Empfelungen zur Berechnung von Tunneln im Lockergestein, *Die Bautechnik*, 57(10), 349-356, 1980.

Nuttens, T., *Tunnel Ovalization Monitoring: 3D Data Acquisition with Laser Scanning and Point Cloud Processing*, PhD Thesis, Ghent University, Belgium, 2014.

Schotte, K., De Backer, H., Van Bogaert, Ph., Nuttens, T. and De Wulf, A., Design Considerations of Segmental Tunnel Linings in Assembly Stage, *Tunnels for a Better Life*, Negro, A., Cecílio, M. and Bilfinger, W. (Eds.), 30, CBT/ABMS, São Paulo, Brazil, 2014.