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Structural response of a tunnel lining to water level fluctuations of a tidal river

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Abstract

The 6 km long Liefkenshoek rail tunnel aims to create a new freight connection in the Port of Antwerp (Belgium) by crossing the River Scheldt and Port Canal. An essential step in the design process of bored tunnel linings is a correct identification of the loads acting on the precast tunnel segments, during and after tunnel drive works. For the Liefkenshoek tunnel, one of the neglected load states acting on the assembled lining proved to be the water level variation of the River Scheldt, corresponding to the tides of the North Sea. The tidal effect causes an oscillating vertical displacement of the tunnel lining up to 10 mm between low and high tide. Outside the river boundaries no significant tidal influence is found, and the transition zone between the stable tunnel sector and the moving part below the river appears to be constrained to a relatively small tunnel section. Thanks to the various components of the complementary monitoring program, consisting of strain, ovalization and levelling measurements, a clear understanding of the structural response to the river tides could be obtained. It was proven that the monitored 10 mm displacements are the result of a vertical translation of the tunnel lining as a whole. Furthermore, the concrete lining shows a uniform compression and relaxation between high and low tide. The corresponding monitored stress changes show a good resemblance with results from simplified analytical calculation. This paper reports in-depth on the methodology of the specific monitoring program and presents the main results and conclusions of the detailed investigation on the effect of the river tides.

1. Introduction

Mechanized tunnelling techniques such as closed-shield tunnelling form an important part of the underground construction industry. Their application offers several advantages in comparison with classic cut-and-cover methods regarding impact on existing structures, noise, vibrations and often financial costs, depending on project-specific parameters. In addition, more and more tunnels are planned beneath various obstacles that leave no alternative construction method but shield tunnelling.

Whether due to severe restrictions towards settlements in highly urbanised areas or as a result of large groundwater pressures, a large number of projects benefits from the closed-face tunnelling technique to overcome the boundaries that once seemed ‘a bridge too far’. One can think of several examples, such as (but not limited to) excavating the subsoil of large metropolitan areas, tunnelling beneath airport infrastructure or crossing busy waterways.

2. Liefkenshoek rail link project

The Liefkenshoek project aims to establish a new railway connection for freight traffic between the left and right bank of the River Scheldt, in the Port of Antwerp, by the end of 2014. This new rail link has a total length of approximately 16 km, of which 6 km was constructed as a twin bored tunnel by two shield-driven tunnel boring machines (TBM) using the mix shield method. The parallel single-track tunnels with an internal diameter of 7.3 m were excavated below the River Scheldt and the Port Canal. Each tunnel ring is 1.8 m wide and consists of seven concrete segments and a smaller keystone, all of 0.4 m thickness in C50/60 concrete quality, according to Eurocode (Boxheimer and Mignon 2009). The geometry of the tunnel rings is shown in Figure 1.

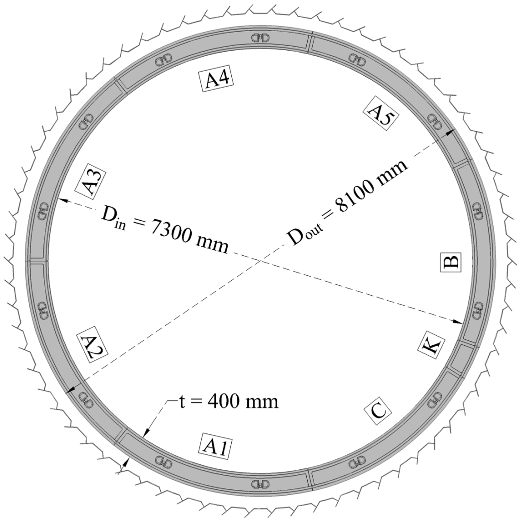

Figure 1 Geometry of the Liefkenshoek tunnel

The crossing of the River Scheldt and the Port Canal required special attention, due to the shallow overburden above the tunnel. Adequate measures were taken to prevent boring face destabilization at these critical sections (Boxheimer and Mignon 2011). The River Scheldt crossing was characterized by a minimal overburden of 9.7 m and a river bed containing silt sedimentation and thick layers of disturbed sediment soil. In combination with the high-water pressures, this led to a very small range between the minimum slurry confinement pressure and the blow-up pressure. Furthermore, during the drilling process, the water level variation of the river, linked to the tides of the North Sea, had to be taken into account. The regular variation of the water level is between +6.0 m TAW and -0.5 m TAW, with TAW being the Belgian reference height level. However, a spring tide with an additional water level variation of 2 m had to be considered as well. As a consequence of the small range between the decisive pressure levels and the quick change of water pressure, the slurry confinement pressure to support the front face had to be adjusted by the TBM operators at a high frequency.

3. Description of the measurement set-up

In each tunnel tube, eight particular cross-sections of the tunnel lining were selected for strain gauge measurements. In general, the distribution of these sections along the tunnel axis allows investigating the effect of several local influences (Schotte et al. 2011b; a), and in particular, one of these sections is located below the centre of the River Scheldt. Each monitored tunnel ring is equipped with several strain gauges, distributed across the ring perimeter. Prior to concrete casting in the prefabrication plant, all segments, except for the smaller keystone, were equipped with two internal strain gauges attached to the inner and outer reinforcement bars in circumferential direction. Immediately after installation of the segments in the tunnel, a third strain gauge was glued to the inner concrete surface of each segment, measuring strains in circumferential direction, corresponding to the internal strain gauges. Immediately after installation of the ring segments in the tunnel under construction, monitoring of the strain gauges was initiated. Over the course of almost two years, strain measurements registered the behaviour of the tunnel lining.

Extensive ovalization measurements using laser scanning were carried out at 14 cross-sections in each tunnel tube, 8 of which coincide with the strain measurements. As a result, the measurement section below the River Scheldt was included as well. With a Leica HDS6100 laser scanner, following the methodology described in Nuttens et al. (2012), an experimental standard deviation of 0.48 mm in actual tunnel conditions was established.

As part of the quality inspection after tunnel construction, regular levelling measurements of the tunnel installations are performed by the design office (TUC RAIL Ltd) along the entire length of the bored tunnel alignment. In order to obtain accurate data of the tunnel level, specific topographical bolts were fixed onto the tunnel segments every 25 tunnel rings. At specified time intervals, the levels of the bolts are measured using a Leica DNA10 digital level with a standard deviation of 0.9 mm per km double levelling. Every monitoring session starts from a fixed reference point, either outside the bored tunnel or at the location of an evacuation shaft (ES), where a link with the surface level can be made. Subsequently, the levels of consecutive bolts are measured one by one, until the target location is reached. Finally, in order to reconnect with the reference starting point, the levelling measurement ends with retracing its steps and registering the bolt levels in the opposite direction. In this way, an accurate topographical system can be established that enables to link the tunnel levels with the reference system above ground.

4. Monitoring results of tidal influence

Levelling measurements performed at various points in time showed a discrepancy up to 10 mm in the monitored levels of the tunnel structure below the River Scheldt. As the difference was too large to attribute to errors in the measurement procedure and as it only occurred below the river, further investigation was advised. Since the River Scheldt showed a variation in water level between the different measurements due to tidal fluctuations, the disagreement in levelling results was attributed to the river tides. In order to obtain full confirmation of this theory, specific strain, ovalization and levelling measurements were combined during a special measurement day on 31 October 2012. On this occasion, the structural response was closely monitored at the location of ring 1500 in tunnel south, situated below the centre of the River Scheldt. In order to observe possible deformations between high and low tide, the combined monitoring session lasted from approximately 8h30 in the morning to 18h30 in the evening. Consequently, the resulting data included the situation at low tide (10h50) and high tide (16h00).In order to allow for multiple measurements in the time interval between low and high tide, only one out of two bolt levels was measured during the special measurement day.

Figure 2 shows the calculated differences in bolt levels between high and low tide. Since ring 1100 was chosen as fixed reference point, the difference at this location equals zero. It can be observed that the tunnel level remains almost perfectly stable in the vicinity of evacuation shaft 7 (ES07), which is constructed as a rectangular shaft of diaphragm walls between both tunnels. A large shift occurs between measurement points at rings 1250 and 1300, which corresponds to the location of the river bank. From ring 1350 to the centre of the River Scheldt at ring 1500, the difference between low and high tide remains steady at 10 mm. These results show that the variation in tunnel level is undoubtedly linked to the tidal fluctuations of the River Scheldt, with a maximum difference of 10 mm occurring between high and low tide below the major part of the river.

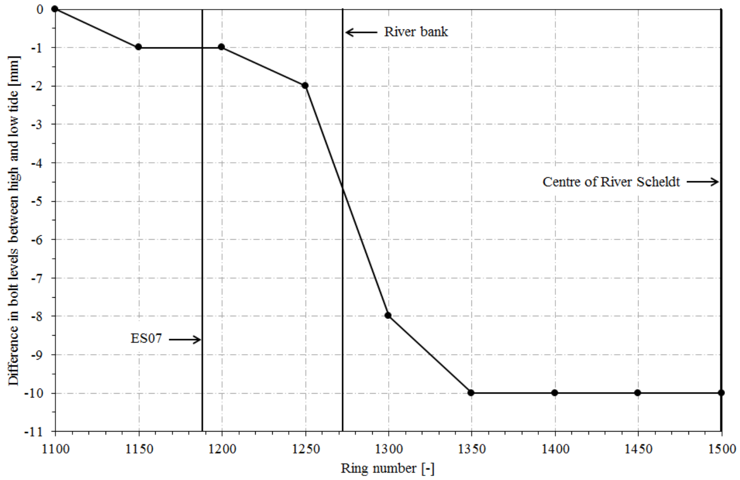

Figure 2 Difference in tunnel level between high and low tide below the River Scheldt (upwards oriented vertical axis).

As corresponding measurement sections were installed in both tunnel tubes at approximately identical locations, strain response could be monitored closely in two sections below the River Scheldt: ring 1497 in tunnel north and ring 1500 in tunnel south. Figure 3 shows the strain results of the active strain gauges in both sections during the scheduled time frame of the special measurement day.

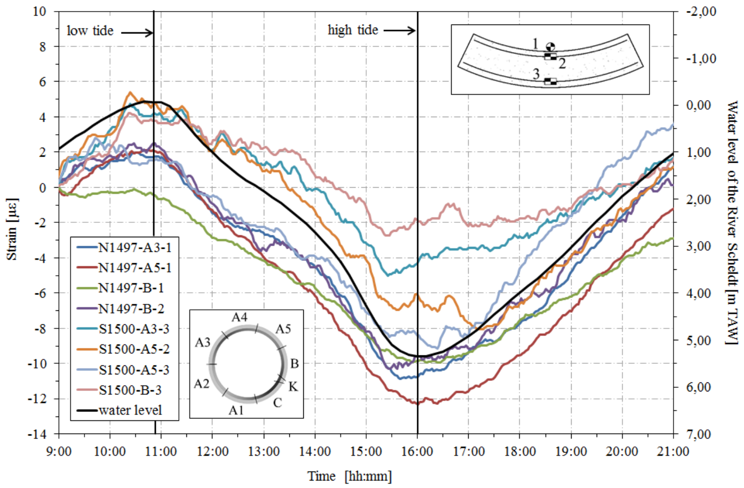

Figure 3 Tidal fluctuation of the strain results below the River Scheldt.

The various graphs in Figure 3 correspond to the various strain gauges installed in ring 1497 in tunnel north and ring 1500 in tunnel south, each indicated by a coloured code as shown in the chart legend. Figure 3 allows a clear observation of the influence of the water level fluctuation of the River Scheldt on the strain results in both tunnel sections. Strains tend to increase at low tide, indicating a relaxation or general decrease in compression of the tunnel rings. A larger head of water at high tide in turn causes a larger uniform compression of the tunnel rings. Notwithstanding a ground cover of about 10 m between the tunnel and the river, which could cause a potential delay of the strain response in correspondence to the rise and fall of the water level, extreme values of the strain curves coincide with low and high tide in the River Scheldt. Consequently, strain results of the tunnel lining show no time shift between the river tides and the structural response. Figure 3 also illustrates that the strain response to the tidal fluctuations is not identical for all strain gauge locations. Figure 4 shows strain results from the measurement section in tunnel north, over the timeframe of one week around one and a half months after ring erection. From this graph, it can be observed that periodic half-daily fluctuations occur in the stabilized strain results due to the tidal effects, without the presence of a general secondary drift in the monitored data. Furthermore, identical behaviour is found for every gauge location, as a confirmation of the results depicted in Figure 3. Increasing compressive stresses at rising water levels apply for all measurement points, indicating that no significant bending moment is induced in the tunnel lining by the tidal fluctuations. In conclusion, the rise and fall of the water level of the River Scheldt only causes a uniform compression (high tide) or relaxation (low tide) of the tunnel lining below the river, based on the strain measurements.

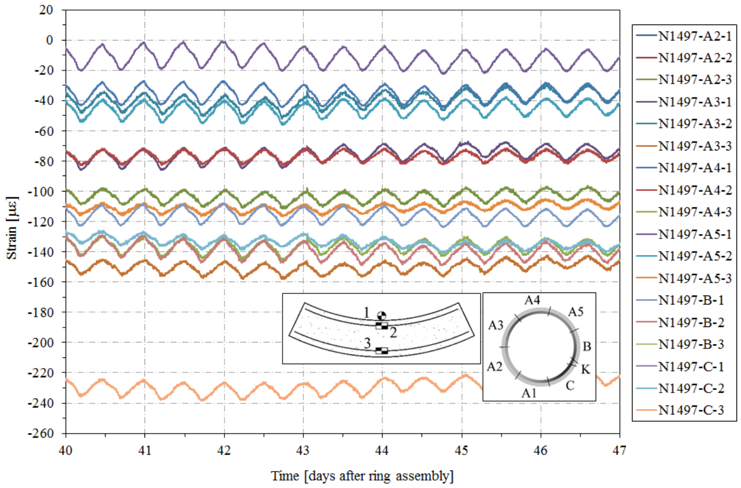

Figure 4 Long-term tidal fluctuation of the strain results below the River Scheldt.

Laser scanning measurements were performed every hour in both tunnels during the scheduled time frame and in tunnel South specifically at least every time the levelling team arrived at the monitored section. Figure 5 shows the comparison of the ovalization measurements at low tide and high tide for ring 1500 in tunnel south.

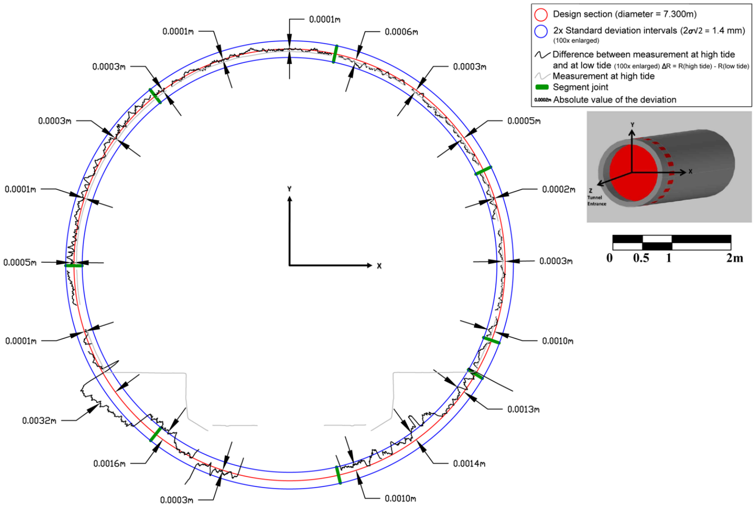

Figure 5 Laser scanning results below the River Scheldt: comparison of measurements at low and high tide.

The difference between both measurements (black) is plotted against the theoretical cross-section (red), taking into account that all deviations are 100 times enlarged. It can be observed that for most of the tunnel section, the plotted differences between the measurements at low and high tide show no significant deviations or changes in shape of the tunnel section. The 95% significance levels of 1.4 mm (blue) can be taken as the threshold for this determination.

5. Conclusion

Levelling measurements of the Liefkenshoek rail tunnel below the River Scheldt exposed a 10 mm vertical displacement of the monitored bolts fixed onto the tunnel lining. After analysis of all monitoring results, this movement proved to be the result of an oscillating vertical translation of the tunnel lining due to the tidal level fluctuation in the River Scheldt. The tidal effect can also be perceived in the strain data of the lining segments in the monitored cross-sections, showing a uniform compression at high water levels corresponding to theoretical values from analytical calculation. Despite stress variations due to river tides remaining relatively small, they might prove unfavourable for the long-term durability of the tunnel lining.

Thanks to the various components of the complementary monitoring program, consisting of strain, ovalization and levelling measurements, a clear understanding of the structural response to the river tides could be obtained. It was proven that the monitored 10 mm displacements are largely the result of a vertical rigid body movement of the tunnel lining, and consequently their impact regarding structural damage is considered to be limited. Nonetheless, a detailed investigation of the confined transition zone between the tunnel sector showing no tidal influence and the affected area below the river appears necessary. Furthermore, as the railway infrastructure is governed by high accuracy levels and low safety margins for deformations, special attention is required. In conclusion, measurements from this study presented a perfect example of how the design process of bored tunnel linings requires a thorough understanding of the project surroundings for a correct and utter identification of the loads acting on the tunnel segments, both during and after tunnel drive works.

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