Assessment of the Tidal Influences on Tunnels based on Different Monitoring Techniques: Laser Scanning, Levelling and Strain Gauges

Nuttens, T.[1], Stal, C.[1], De Backer, H.[2], Schotte, K.[2], Van Bogaert, P.[2] and De Wulf, A.[1]

[1] Ghent University, Faculty of Sciences, Department of Geography, Krijgslaan 281 (S8),
B-9000 Gent, Belgium, Web site: http://geoweb.ugent.be/data-acquisition-3d
E-mail: Timothy.Nuttens@UGent.be, Cornelis.Stal@UGent.be, Alain.DeWulf@UGent.be
[2] Ghent University, Faculty of Engineering and Architecture, Department of Civil
Engineering, Technologiepark Zwijnaarde 904, B-9052 Zwijnaarde, Belgium,
Web site: http://www.ugent.be/ea/civil-engineering/en, E-mail: Hans.DeBacker@UGent.be,
Ken.Schotte@UGent.be, Philippe.VanBogaert@UGent.be

Abstract

For the first time in Belgium, an integrated monitoring campaign based on laser scanning, levelling and strain gauge measurements was carried out to assess the deformations of a recently built twin tube tunnel, giving deeper insights in the deformation pattern under influence of river tides. A selected section in one of the tunnel tubes of the ‘Liefkenshoek Rail Link’ project below the River Scheldt (Antwerp, Belgium) was measured in 2012 during a tide cycle. Previous levelling measurements on levelling bolts in the tunnel showed a difference in height of up to 10 mm between low and high tide and during a tide cycle. This difference was the motivation to verify the measurements using different techniques.

A new series of levelling measurements during the integrated monitoring confirmed the earlier findings and simultaneous strain gauge measurements showed a significant difference in strains between low and high tide. A deformation of the tunnel section itself during each twice-daily tide cycle, resulting in an ‘egg’ or ‘pumpkin’ shape, could hold large risks for both the strength and durability of the tunnel structure. However, the laser scanning results clearly showed that there were no significant deformations of the tunnel section during the tide cycle, determined with an experimental standard deviation smaller than 0.5 mm, the detected displacements thus being of the rigid body type. This more thorough view on the deformation pattern improves the risk assessment and long term consequences for the tunnel structure.

Key words: Tunnel structures, tidal influences, monitoring, laser scanning

1 INTRODUCTION

During recent years, (terrestrial) laser scanning has been applied as a technique to measure large infrastructures. The measurement speed, high achievable accuracy and possibility to obtain a detailed and complete 3D image of complex objects are important advantages contributing to its growth (Han et al., 2013).

Currently, terrestrial laser scanning is being used frequently for high accuracy deformation measurements of tunnels, either during a long-term monitoring program or during the construction phase (Argüelles-Fraga et al., 2013; Lam, 2006; Lindenbergh et al., 2005; Nuttens et al., 2013; Pejić, 2013; Yoon et al., 2009). Other examples of tunnel deformation measurements based on laser scanning can be found in (Delaloye et al., 2011; Fekete et al., 2010; Gordon & Lichti, 2007; Molins & Arnau, 2011). As will be discussed in this paper, the challenge is to combine highly accurate laser scanning and cross-section monitoring with other applied monitoring techniques to assess difficult or critical deformation patterns. The combination of simultaneous levelling measurements, strain gauge registrations and laser scanning measurements in the Belgian tunneling project in this research is an important step forward in the awareness of the relevance of an integrated monitoring strategy for large infrastructural projects. Laser scanning not only offers a full 3D view of the tunnel construction, an optimal use of the data also allows detecting other aspects of the tunnel's deformation, resulting in a better judgment on the risks of the occurring deformations.

2 LIEFKENSHOEK RAIL LINK PROJECT

The 'Liefkenshoek Rail Link' project (2010-2014) established a new railway connection for freight traffic between the left and right bank of the River Scheldt in the Port of Antwerp (Belgium). This new railway connection has a total length of approximately 16 km, of which 6 km consists of two twin tunnels ('Tunnel North' and 'Tunnel South'), constructed in 2010-2011 by two shield driven Tunnel Boring Machines (TBM) using the mixshield method (Van Bogaert, 2009). This newly bored tunnel complex crosses two waterways (River Scheldt and Canal Dock/Port Canal), the soil cover above the tunnel being rather shallow (3 to 10 m) (Figure 1). The two newly bored tunnels have an inside diameter of 7.300 m, the concrete tunnel segments having 0.400 m thickness. The longitudinal size of each tunnel ring is 1.800 m, each tunnel ring consisting of seven concrete segments and one smaller key stone (TUC Rail, 2010).

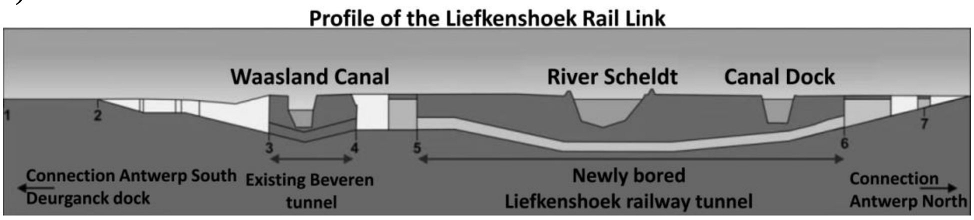

Figure 1 Overview of the 'Liefkenshoek Rail Link' project

3 TIDAL INFLUENCE ON THE TUNNEL CONSTRUCTION

The River Scheldt has a direct connection with the North Sea and is therefore affected by the tidal water level variation in the North Sea. Twice a day, the River Scheldt reaches its lowest and highest water level, with an average difference in water level of about 5.5 to 6 meter. This difference in water level between ebb and flood can increase with another 2 meter during spring tides. The continuous variation in water level and water pressure had to be taken into account during the drilling works of both tunnel tubes and as recent levelling measurements at the final stage of the works have shown, the influence of the variable water pressure still continues.

For the levelling measurements during the construction period of the tunnel tubes, specially installed topographical bolts were measured every 25 tunnel rings using a Leica DNA10 digital levelling instrument, with a specification of 0.9 mm standard deviation on height measurements per 1 km with the use of an invar staff. Measuring these bolts at different moments in time (starting from a fixed reference height level), showed variations up to 10 mm in height between the various measurement sessions for several bolts below the River Scheldt. After extensive investigation of several levelling measurement series, a relation was found between the change in level of the topographical bolts and the tidal movements of the River Scheldt.

To further investigate this relation between the measured elevations of the topographical bolts, the water level variations and the influence of these water level variations on the whole surface of the tunnel rings, integrated monitoring was carried out, combining simultaneous laser scanning measurements, strain registrations and leveling measurements. The combinations of these techniques and their respective results can confirm or exclude some deformation patterns and their causes, leading to a thorough knowledge of the deformations of the tunnel rings and their possible long term consequences.

4 INTEGRATED MONITORING

4.1 LEVELING MEASUREMENTS

The first part of the monitoring program consisted of levelling measurements, performed hourly in one of the tunnel tubes (‘Tunnel South’). Starting from a stable reference point, levelling bolts were measured until the monitored tunnel section in the middle of the River Scheldt in ‘Tunnel South’ was reached. The results of these measurements are presented in Figure 2. The graph in Figure 2 is limited between ring number 1250 and 1500 as this area is subject to the largest differences between low and high tide.

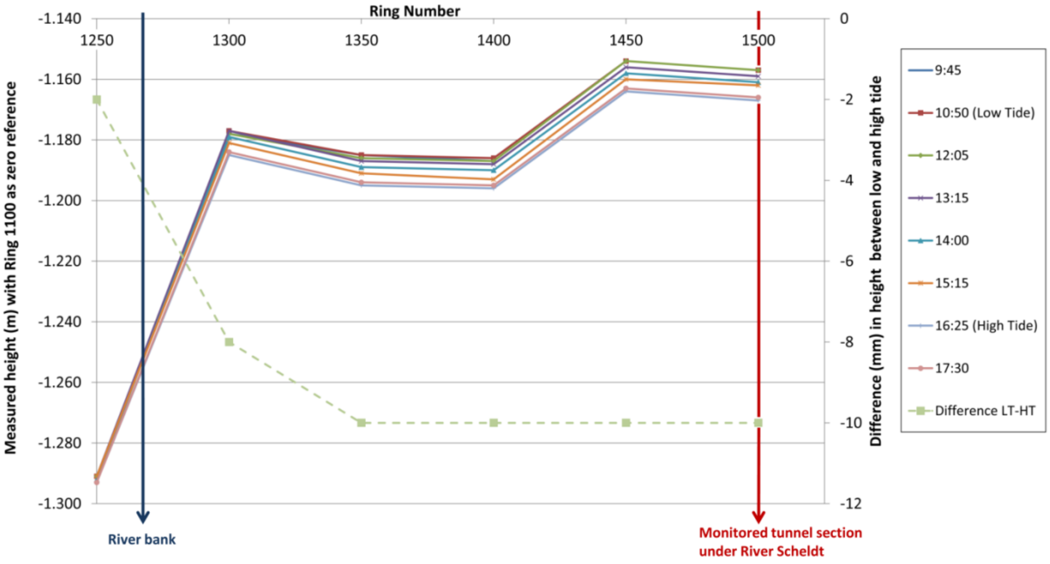

Figure 2 Measured heights of the levelling bolts during the different measurement series and the differences between low and high tide (ring number 1250 to 1500)

The graph (Figure 2) clearly shows a variation in the height of the bolts below the River Scheldt between the series of measurements and thus between the different tide levels. The variation increases towards the deepest area below the River Scheldt, until the center of the river is reached (Ring 1500). Moreover, the absolute height values of the monitored bolts wane between low and high tide and increase again after the high tide is passed, indicating the largest pressure on the tunnel structure at high tide. The dotted line in Figure 2 and the right vertical axis indicate the difference in height value between low and high tide for every measured leveling bolt. At ring 1250, the difference between low and high tide is maximum 2 mm, where this difference at ring 1300 reaches already 8 mm. After ring 1300 this difference slowly increases to 10 mm difference at ring 1500. This shows that the largest jump in difference between low and high tide can be located between ring number 1250 and 1300, corresponding to the transition between the left river bank and the River Scheldt.

4.2 STRAIN GAUGE MEASUREMENTS

Simultaneously with the levelling measurements, the integrated monitoring used strain gauge measurements to detect the influences of the various loading conditions on the concrete segments of the tunnel rings. More information about the location of the strain gauges, the installation procedure and results of the monitoring during the construction phase can be found in (Schotte et al., 2013). The strain measurements during the integrated monitoring show an increase of the strains at low tide, indicating a general decrease of compression of the tunnel rings. Between low tide and high tide, the growing water pressure above the tunnel section causes a larger compression of the tunnel rings.

4.3 LASER SCANNING MEASUREMENTS

The third part of the monitoring consisted of laser scanning the monitored tunnel section every hour and additionally on the specific low and high tide moments. Following the developed measurement methodology as described in (Nuttens et al., 2014), a Leica HDS6100 phase-based laser scanner is set up on a tripod in the middle of the tunnel section, measuring the tunnel surface with an average point density of 4 mm on 6 m distance (Figure 3).

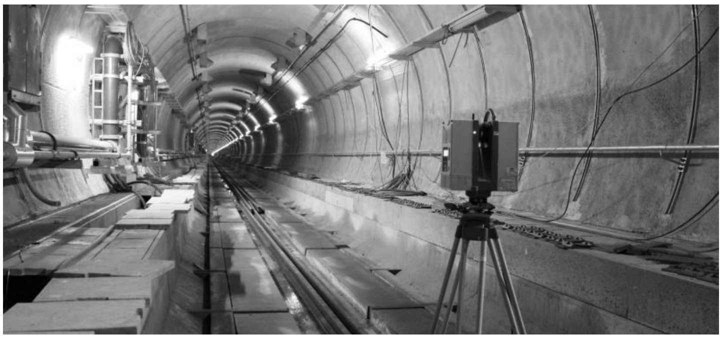

Figure 3 Laser scanner setup

To monitor the tidal influences on the tunnel sections, the laser scanning measurements at low and high tide were processed. After filtering the point cloud, a best-fit cylinder is determined and a cross-section is defined based on a mesh of the section’s concrete surface and through a fixed reference marker. More details about the processing methodology can be found in (Nuttens et al., 2014). For the low and high tide measurements, the cross-sections are then compared to detect any deviations from ovalisation. As detailed below, there was no statistically significant difference between both measurements. To confirm these results, a measurement between low and high tide was also processed (‘Middle measurement’). Based on the project requirements of 0.5 mm accuracy, which was achieved by the experimental standard deviations, the significance level for the comparison between two measurements is set at $2\sigma\sqrt{2}$ = 1.4 mm. Figure 4 shows the difference between the measurement at low tide and the measurement at high tide. This difference, represented by the black line (100 times exaggerated) and set out to the reference of the design radius, clearly falls within the significance level boundaries (two outside blue circles). Taking only the upper part of the section into account (the circular part above the rail bed), the arithmetic mean difference (average of the differences) between both measurements is 0.0 mm and the absolute mean difference (the average of the absolute differences) is 0.3 mm. If the part of the rail bed is also taken into account, the values are 0.1 mm and 0.5 mm for respectively the mean difference and the absolute mean difference.

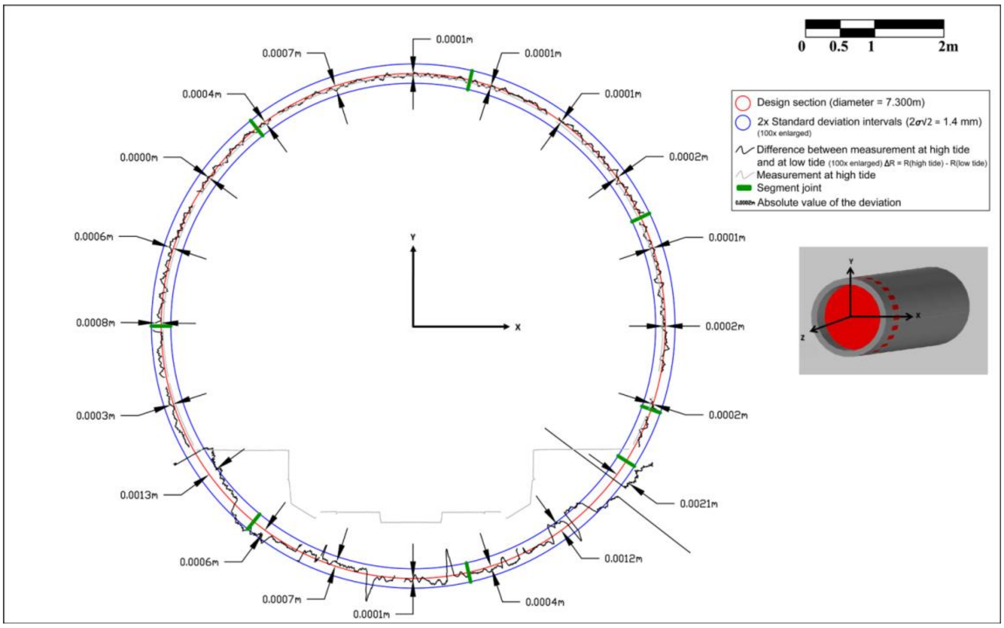

Figure 4 Comparison between the measurement at low and high tide

5 CONCLUSIONS

The levelling measurements during the above described extensive monitoring program confirmed that the tunnel sections below the River Scheldt are influenced by the tidal water fluctuations. The measurements of the leveling bolts indicate a difference in height between low and high tide of up to 10 mm, measured from a fixed reference point outside the influence of the water level variations. The strain gauge measurements during the integrated monitoring show a difference in strains between low and high tide, also confirming that the tunnel structure undergoes a significant influence of the river tide. Based on the 10 mm height difference between low and high tide and the strain gauge results, the question remains whether this height difference is due to a deformation of the tunnel section itself or due to a general vertical rigid body movement. A deformation of the tunnel section itself during each tide cycle, resulting in an ‘egg’ or ‘pumpkin’ shape, could hold large risks for both the strength and durability of the tunnel. Complementing these levelling and strain gauge results with the highly detailed and accurate 3D laser scanning point clouds, measured at successive stages of the tide cycle, gives new insights on the actual deformation pattern of the tunnel structure. The cross-sections derived from the laser scanning point clouds show that there is no significant deformation of the monitored tunnel section during the tide level variations.

The combination of the results of the different simultaneous measurement techniques points towards the conclusion that the tunnel structure undergoes a vertical rigid body movement caused by the changing water pressure and no deformation of the shape of the tunnel sections themselves occurs, reducing the critical character of the deformation and actions to undertake. This more thorough view on the deformation pattern improves the risk assessment of the deformations and changes the idea of the possible long term consequences.

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