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Methodology for the ovalization monitoring of newly built circular train tunnels based on laser scanning: Liefkenshoek Rail Link (Belgium)

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ABSTRACT

The ovalization monitoring methodology based on laser scanning, developed during two recent tunneling projects in Belgium, elaborates a clear processing workflow and easily interpretable deliverables with sub-millimeter accuracy. The extensive and systematic monitoring coverage during the first three months after construction of a circular tunnel structure delivers an important contribution to the understanding of the tunnels' behavior between the construction phase and the final stabilized shape. The observed differences of the average radius values generally show a decrease in the first week after ring erection and a stabilization of the tunnel structure during the following weeks. The results of such a systematic monitoring program allow the contractors or engineers involved to validate the theoretical models and to compare with the actual behavior of large diameter shield tunneling in soft soil. This is highly valuable, because very few measurements are available at this early stage of a tunnel construction to evaluate the performance and accuracy of such theoretical models.

1. Introduction

Monitoring the stability of a civil technical structure is a challenging task, already being addressed for a long time in literature [1]. The use of total stations for monitoring constructions is still being applied in a wide range of applications [2,3], but these measurements deliver only a small set of points that can be monitored in the limited time frame available for the measurements. Research is continuously focusing on techniques that can be used for the detection of centimeter or sub-centimeter deformations of constructions. Examples are: kinematic GNSS measurements for bridge deflections [4], laser scanning in 2D or 3D mode for the monitoring of bridges or harbor locks [5,6], tunnel monitoring [7–10], measuring beam deflections [11] or monitoring cultural heritage monuments [12–14]. In recent years, terrestrial laser scanning (TLS) is more and more being applied for the acquisition of accurate and dense 3D datasets, because a high scanning speed and high accuracy offer laser scanners significant advantages compared to more traditional techniques. However, the necessary ad hoc processing of the laser scan data and the price of the equipment remain important barriers for a practical and straightforward implementation of laser scanning in a lot of projects [15,16]. Digital photogrammetry is another widely applied technique, but this requires sufficient lighting conditions and texture on the objects surface [17,18], requirements that cannot be guaranteed in tunnel construction projects. Laser scanning needs no specific lighting conditions and can deliver millions of accurate 3D coordinates in a limited time frame, making this a preferred measuring technique for the recent Belgian tunneling projects discussed in this paper.

Recent developments presented in literature describe different tunnel deformation analysis techniques based on laser scanning. As described in Ref. [8], static or mobile scanning systems are used to compare the measured construction to a fitted surface, even when the structure includes some curved parts. Detected damage, cracks or deformations with this technique are limited to 2 mm diameter objects or larger [8]. Other techniques based on the comparison of tunnel cross-sections suggest different possibilities to place cross-sections of different epochs in a common coordinate system. In Ref. [15], extra total station measurements are used to determine the coordinates of a number of reference targets and also in Refs. [19,20], in situ control features are used to define a common datum between measurements at different epochs. However, these methodologies not only involve additional time consuming measurements, they also do not cope with a displacement of the reference features themselves caused by a deformation of the tunnel structure between different epochs. Moreover, no clear definition of the tunnel axis is given in these methodologies and the cross-sections are based on the point cloud of the measurements, by interpolating the point cloud to obtain a regular point grid on the cross-section or using a buffer size left and right of the cross-section location, resulting in achievable accuracies of millimeter level [19–21]. The methodology developed by the authors includes not only a definition of the tunnel axis based on a best-fit cylinder, but also a meshing step in the workflow to determine the cross-section based on a triangulated surface instead

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of the original point cloud, taking the findings in Ref. [10] in mind that it is important to compare surface-based cross-sections instead of point-based cross-sections. Additionally, the cross-section evaluation is done using thousands of points, which is necessary to get a fully detailed picture of the profile [22], and the methodology presented in this paper results in a much higher accuracy (sub-millimeter level). Thanks to this highly detailed picture of the cross-sections, the segment joints are easily detectable. Complying with the need for segmental deformation analysis as expressed in Refs. [23,24], this makes further analysis of the individual segments easily possible, also during the settlement of the tunnels in the first weeks after construction. The presented methodology covers the measurements on site, a clear processing of the data and the elaboration of easily interpretable reports and plots afterward. Moreover, the developed methodology also includes a measurement setup in the head of the Tunnel Boring Machine (TBM) just after the construction of a tunnel ring which allows limiting the downtime of the drilling works. These measurements are very valuable, because few systematic measurements in such an early stage of tunnel construction are available to evaluate the performance or accuracy of theoretical deformation models.

The research presented in this paper focuses on the application of terrestrial laser scanning for ovalization measurements of newly drilled concrete tunnels from the moment of ring assembly until three months after construction. The extensive and systematic monitoring coverage during this time frame delivers an important contribution to the understanding of the tunnels' behavior between construction and its stabilized shape. The two tunnel monitoring projects on which this research is based are the first projects in Belgium in which laser scanning was used to systematically monitor the ovalization of multiple tunnel sections under construction. In the 'Diabolo' project (Zaventem — Brussels, Belgium), the use of laser scanning for this type of monitoring was tested and implemented [25]. In the 'Liefkenshoek Rail Link' project (Antwerp, Belgium) that followed, the workflows were optimized and the processing of the datasets further elaborated. In addition to laser scanning, strain gauge measurements were also performed on some of the same sections in order not only to measure the strains of the individual concrete segments, but also to investigate the link between the strain measurement results and the results of the laser scanning measurements [26]. The simultaneous data of both laser scanning and strain gauge measurements enables combining the conclusions from both methods and thus improving the knowledge of tunnel behavior in in situ conditions.

Section 2 describes in detail the recent 'Liefkenshoek Rail Link' tunnel monitoring project in Belgium. Section 3 explains the measurement equipment, measurement workflows and processing methodology. The results of the monitoring measurements are presented in Section 4, followed by a discussion section and a final Conclusions section.

2. Tunnel monitoring project: Liefkenshoek Rail Link (Belgium)

The 'Liefkenshoek Rail Link' project establishes a new railway connection for freight traffic between the left and right bank of the River Scheldt in the Port of Antwerp. This new connection has a total length of approximately 16 km, of which 6 km is constructed with two new side-by-side tunnels by two shield driven TBMs using the mixed shield method [27]. This new bored tunnel complex crosses two waterways (River Scheldt and Canal Dock/Port Canal). Under the Waesland Canal, an already existing tunnel is integrated in the railway connection. An overview of the profile of the railway connection can be seen in Fig. 1.

Along the tunnel's route, the soil stratification has a general downward slope from the West to the East, indicated by the Boom clay layer boundary in Fig. 1. The left (West) bank of the River Scheldt consists of sandy layers until a depth of 4 to 6 m. Under these layers, a quaternary soil made out of soft clay is present. This clay layer does not occur on the right bank of the river. Further below, there are layers of the tertiary era containing silt and a mixture of fine sand and clay. At larger depth, the soils consist of Boom clay (indicated in Fig. 1 with green dashed line), acting as an impermeable soil layer. The tunnel's trajectory mostly runs through the tertiary sands, but at its deepest point (below the River Scheldt) it also runs through the Boom clay layer. The TBM's passage below the River Scheldt and the Canal Dock needs special attention and extra preparation works which do not allow accessing the boring chamber or replacing parts of the cutting wheel while crossing those waterways.

The two newly drilled tunnels have an inside diameter of 7.300 m and the concrete tunnel segments have a thickness of 0.400 m. The longitudinal size of each tunnel section is 1.800 m and each tunnel section is made out of seven concrete segments and one smaller closing stone [28]. In each tunnel tube ('Tunnel North' and 'Tunnel South'), fourteen tunnel sections were selected to be monitored, including a specific tunnel section in each tube under the River Scheldt and the Canal Dock.

In this tunnel project, seven moments in time were defined on which the selected tunnel sections had to be measured: the 'reference measurement' immediately following construction of the tunnel section; a measurement every week during the first month after placement (control measurements 1 to 4) and measurement two and three months after placement (control measurements 5 and 6). The cross-sections are compared with the design shape and, if applicable, also with the reference measurement and the previous control measurement of that tunnel section. These comparisons are summarized in tables and visualized on different plots, which also indicate the areas where possible significant deformations appear.

The ovalization monitoring with laser scanning measures the changes in position of the individual segments of the tunnel section. The deformations of the segments themselves however, fall outside the

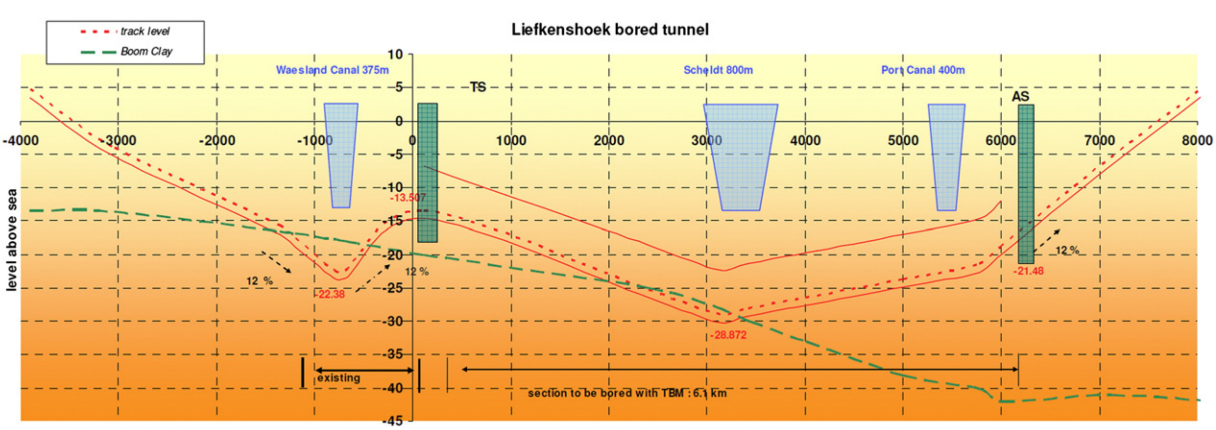

Fig. 1. Longitudinal profile of the bored tunnel in the 'Liefkenshoek Rail Link' project (according to Ref. [27]).