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On the effects of the TBM-shield body articulation on tunnelling in soft soil

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Abstract

When a Tunnel Boring Machine (TBM) is driven in soft soil, the TBM-shield constantly interacts with the surrounding soil profile excavated by the cutting wheel. The interaction pattern of shield-soil interface displacements determines compression and extension sectors in the surrounding soil. Soil compression is generated when the shield displaces the excavated profile in outward direction; soil extension happens when the shield fits inside that profile. This aspect of TBM behaviour, referred to as shield-soil kinematical interaction, has been demonstrated in a recent study investigating the monitoring data from the Hubertus tunnel in The Hague. The TBM used at the Hubertus tunnel was not equipped with a shield-body articulation. The articulation, designed to limit the undesired shield-soil interactions of the kind described, was present in the TBMs used at the North-South metro line in Amsterdam. This study aims to quantify the consequences of using a shield articulation in terms of shield-soil kinematical interactions. The study, comparing the results from the Hubertus and the North-South line tunnels, revealed remarkable differences, although other discriminating aspects have to be accounted for. The fundamental understanding of the kinematical interactions is crucial to building reliable numerical models for TBM driving in soft soil.

Keywords: TBM, kinematics, shield-articulation, interaction

1 INTRODUCTION

During the last decade advanced numerical models were developed describing the staged construction process of mechanised shield tunnelling [3]. Those models, usually accounting for detailed aspects such as TBM features, operational choices, and process fluids' handling, can potentially lead to tailored predictions on the effects of tunnelling in soft soil [2]. However, the current understanding of the interaction between the slurry-shield TBMs and their surroundings does not appear sufficiently detailed yet to be fully captured by those models [1]. It is clear, however, that the shield-soil interaction, and especially the ground displacement around the shield periphery, gives a significant contribution to the overall soil deformation [4]. Other aspects such as soil excavation, face support strategy, tail-void grouting, grout consolidation, and tunnel lining deformation contribute as well to the final deformations, but are not investigated here.

This paper focuses on the physical interaction between a TBM-shield driving in soft soil and its surroundings. A model capturing several aspects of the kinematic behaviour of a TBM will be presented. This has been verified by comparing the TBM monitoring data obtained during the construction of the Hubertus Tunnel, a double-tube road tunnel in The Hague, and of the North-South line metro tunnel in Amsterdam. The study revealed differences in terms of amplitude and spatial distribution of the ground displacement around the shield periphery as they occurred in practice. However, other discriminating aspects such as shield diameter and geometry and alignment's curvature have to be accounted for. The results suggest that the fundamental understanding of the kinematical interactions between a TBM and its surroundings is crucial to building reliable models for TBM driving in soft soil.

2 REFERENCE PROJECTS

2.1 The Hubertus tunnel – The Hague

The Hubertus Tunnel was constructed between 2006 and 2007, and consists of two parallel tubes, north and south, 1666.70 m and 1653.48 m long, respectively. Each of the two 9,400 mm diameter tunnels contains two car lanes. Situated in a residential area, the tunnel passes close to the foundations of some houses and in part underpasses several low buildings on a military barracks. The non-articulated

Hydroshield-type TBM used was 10,235 mm long, with a front diameter of 10,510 mm, and a rear one of 10,490 mm. A standard radial overcutting of 10 mm was also used. The cutting wheel was supported by a longitudinally displaceable spherical bearing. The tail-void grouting system consisted of six injection openings, of which only the upper four were actually used. The final concrete lining was constructed with 2 m long rings with an external diameter of 10,200 mm. The theoretical tail void thickness was 165 mm. As in most bored-tunnel projects, overcut, shield length and tapering had been optimized according to the alignment's sharpest curve. The smallest curvature radius was in the south alignment and amounted to 542.300 m. The tunnel tubes were bored from east towards west and the sharpest curve was in leftward direction. The deepest point of the tunnel axis was located 27.73 m below surface. The tunnel was mainly driven through dune sand consisting of well packed silty sands and sandy silts with some clay. The tip resistance q_c of the cone penetration tests ranged between 10÷40 MPa in the layer crossed by the tunnel [5].

2.1 The North-South line tunnel – Amsterdam

The eight single-track bored tunnels serving the new North-South metro line were constructed between April 2010 and December 2012 with four twins slurry-shield TBMs. The analysis will focus on only one of the tunnels, namely the eastern one of the two connecting Amsterdam Central Station with the upcoming Rokin Metro Station. The tunnel, with a length of 723.90 m, was bored from north towards south, and its sharpest curve with a curvature radius of 240 m was bored in leftward direction. The tunnel crosses the very heart of Amsterdam, and although the alignment is entirely located underneath public roads. At several locations, the excavation occurs as close as 3 m from the foundations of adjacent historical buildings founded on wooden piles. The Hydroshield-type TBM used was 7,920 mm long, equipped with a mid-length articulation feature able to provide an extension of additional 200 mm, equivalent to an articulation angle between front and rear sectors of about 1.82°. The shield front part had a diameter decreasing from 6,880 mm to 6,875 mm, and the rear part an even diameter of 6870 mm. The cutting wheel, also supported by a longitudinally displaceable spherical bearing could be completely retracted within the TBM-shield, but also shifted in front of it, with the capability to produce a radial overcutting of 18.6 mm. The tail-void grouting system consisted of six injection openings distributed along the tail circumference and constantly used during drive. The final concrete lining was constructed with 1.5 m long rings with an external diameter of 6,500 mm. The theoretical tail void thickness ranged from 208.6 mm to 190 mm. The deepest point of the tunnel axis was located at -23.946 m N.A.P. (Dutch Reference System), and approximately 25 m below surface. The tunnel was mainly driven through the so-called second sand layer, consisting of relatively densely packed, moderately coarse sand. The tip resistance q_c in that sand layer ranged between 20÷30 MPa.

2.2 TBM guidance system

The combination of measuring devices and reference points located either inside the shield and along the lining in place provides position and spatial orientation of the TBM. The driving system is based on two virtual points of the shield which are supposed to follow the planned tunnel alignment. Both lay along the longitudinal axis of the shield, the first one (front), in the plane of the shield face, and the second one (rear) around the mid-length of the shield (RPF and RPR in Figure 1, respectively).

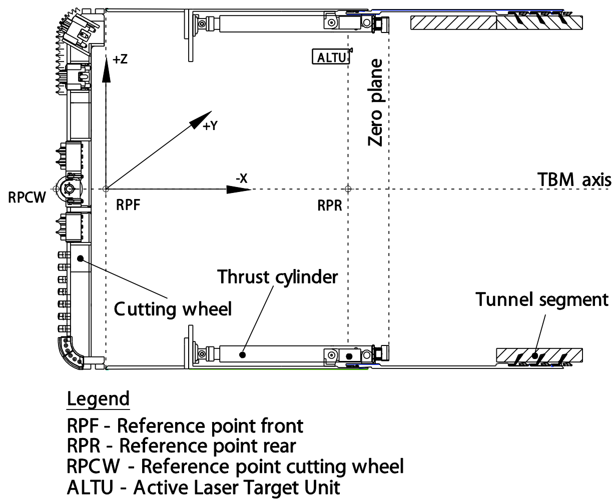

Figure 1: Shield positioning system: reference points and measuring devices (courtesy of VMT GmbH)

Every few seconds the monitoring system provides to the TBM operator the horizontal and vertical deviations of the reference points from the planned alignment. Positive values are arbitrarily given to rightward and upward deviations. Other derived values were also provided (e.g. tendencies, pitch, roll, yaw).
Machine operators constantly aim to follow the planned alignment with both target points. However, this is not always possible as it sometimes requires high steering forces, therefore increasing the risk of damaging the concrete lining already in place. In those cases it may be preferable to advance with a skewed orientation of the machine when this involves smaller driving forces. The skewing required for a smooth driving may differ in direction and amount along the alignment, and its quantification is expected to provide a useful insight into the interaction of the TBM-shield with its surroundings.

3 KINEMATIC MODEL FOR A TBM

3.1 Theoretical model

As seen, the motion of a TBM-shield can be fully described by the consecutive positions occupied by two of its points (if roll is disregarded). Additionally, the motion of an undeformable rectangle (i.e. a simplified cross section of a TBM) driven along a circular path with constant curvature is described by a centre of rotation, a curvature, and the angle between the curvature radius and the rectangle. Different combinations of these elements lead to different motion paths. When the centre of rotation is connected to first quarter (front-half) of the bottom side, at the top side a phase of relaxation is followed by the recompression of the pre-relaxed surrounding soil. After that, the outward drifting of the rear half of the rectangle displaces the surrounding soil beyond the range disturbed by the passage of the first half. On the bottom side an opposite behaviour is observed.
This configuration most closely models the theoretical TBM steering system, in which RPF and RPR are meant to follow the design alignment, and the observed TBM behaviour. Although the exactness of this description is discussed later, the general trend holds that the method of steering strongly influences the interaction with the surrounding soil and compression-relaxation (or unloading-reloading) cycles of the soil around the shield may occur particularly in curves. Furthermore, a certain

degree of drifting of the machine tail may be expected given the “advanced” position of the rear reference point (RPR).

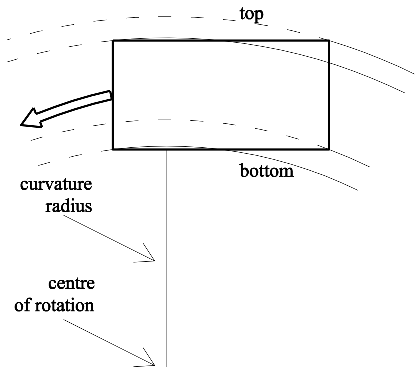

Figure 2: Centre of rotation connected to the mid-point of the first half of the bottom side

3.2 Logged-data based model

A similar study of the TBM’s kinematic behaviour with respect to the surrounding soil was conducted based on the observed positioning data. The horizontal and vertical deviations from the planned alignment of the front and rear reference points were processed such as to obtain the shield’s position and orientation at each tunnel advance. At each advance the actual position of the shield could be compared with the excavated soil profile, and this comparison allowed one to quantify the displacements induced by the advancing shield. The excavation profile has in turn been obtained as the record of the positions incrementally occupied by the cutter head as the TBM advanced. For simplicity, the shield has been assumed non-deformable. Given the soil conditions and the shield features, this condition appeared reasonable for the front part of the shield, but is indeed less perfect for its tail. The numerical model implemented in MATLAB showed to be able to quantify the amount and distribution of the displacements induced by the advancing shield on the surrounding soil.

3.3 Calculation of the interaction displacements

In section 3.1 it was shown that the theoretical drive of a TBM leads to sectors of the shield where the surrounding soil is compressed, and others where it is extended. Such behaviour was also expected during the drive of the actual TBMs. To demonstrate that it proved useful to compare the relative position of the shield-skin at each advance stage with respect to the excavation profile, that is the combined tracks of the cutting wheel and of the cutting edge. Comparing the relative position required to calculate at each advance step of the TBM the relative distance between the discretized grids of the shield and of the excavation profile. Additionally, specifying which of the two was external (or internal) allowed to distinguish between soil compression and extension conditions. These relative displacements were referred to as shield interface displacement.

4 RESULTS

Two useful values in shield-tunnelling are the horizontal and vertical tendencies. Those are obtained as the difference per unit length of the horizontal and vertical deviations of the shield reference points from the theoretical alignment. The tendencies are an indication of the relative positioning of the shield as compared to its theoretical one at each advance stage. As higher the tendency, as more accentuated the yawing/pitching behaviour of the shield. For instance, the horizontal tendency $T_h = \left(d_{h,RPF} - d_{h,RPR}\right)/d_{RP}$ is defined as:

$$T_h = \left(d_{h,RPF} - d_{h,RPR}\right)/d_{RP},$$

where $d_{h,RPF}$ is the horizontal deviation of RPF, $d_{h,RPR}$ the horizontal deviation of RPR, and d_{RP} is the distance between RPF and RPR.

It is often observed that the tendencies vary a lot even between parallel tubes closely spaced, even when bored with the same TBM. This suggested the working hypothesis, adopted hereafter, for the tendencies to be at the same time a picture of the actual driving behaviour of the shield, but also the combination of constructive, measuring, and geological uncertainties not easy to spot and isolate. It is assumed for each TBM to have its intrinsic tendencies, and those were established during the driving of straight sectors. Those are then assumed as reference values. The deviations from the reference values were studied as representative of the actual behaviour of the shield.

Figure 3 reports the shield-soil horizontal kinematical interactions in the Hubertus tunnel Southern tube at the tunnel spring. The sectors -1660.000 ÷ -1160.200 and -1072.200 ÷ -580.490 are straights, the sector -1160.000 ÷ -1072.200 is in a leftward curve with a radius of 1000 m, and the sector -580.490 until the end is in a leftward curve with a radius of 550 m. Positive values of shield-soil interaction represent extension of the soil at the passage of the shield tail, negative values represent compression. The sectors where the soil is compressed are limited. Also limited is the compression rate, always below 20 mm. In the 550 m curve there is a trend for the shield right side to adhere to the excavated profile with modest compressions. Conversely, in the second straight sector the shield left side appears to adhere well to the excavated profile. The reasons for this behaviour are to be investigated further. In the first and second sectors the shield appears well positioned in the middle of the steering gap, with the interaction mostly fluctuating within the bandwidth +10 ÷ +30 mm. The positioning of the shield right in the middle of the steering gap would result in an even interaction rate of +20 mm.

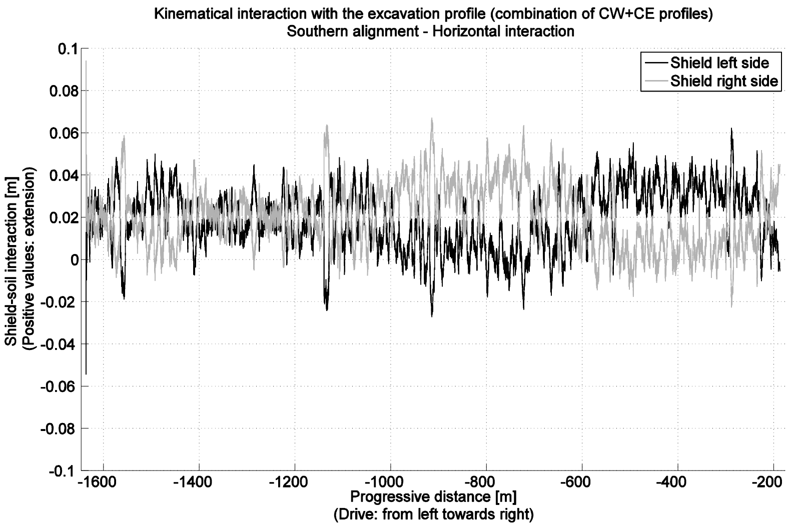

Figure 3: Shield-soil calculated horizontal kinematical interactions; Hubertus tunnel – Southern tube

Figure 4 reports the shield-soil horizontal kinematical interactions in the eastern alignment of the North-South line tunnel at the level of the tunnel spring. The study covers the sector from Central Station to the Rokin new metro station. The drive until advance +220 follows first a rightward then a leftward curve both with a curvature radius of 325 m. The alignment proceeds then straight until advance +446, where a leftward curve with a radius of 240 m begins. In the first sector, in the rightward curve (0 ÷ +85) overcutting is used and the interactions stay almost always positive (negative peaks are not physically possible due to the presence of frozen soil and are to be further investigated). In the leftward curve (+85 ÷ +220) compressions up to 40 mm are observed. In the second sector the shield drills very well balanced within the steering gap, keeping mostly evenly distributed positive values of interaction. In the third sector the presence of the sharp curve is reflected in the soil compression observed at the right-hand side. Also in the same curve it is possible to identify where overcutting has been used, especially in the sector +515 ÷ +530. When that is the case, both right and left interactions become positive.

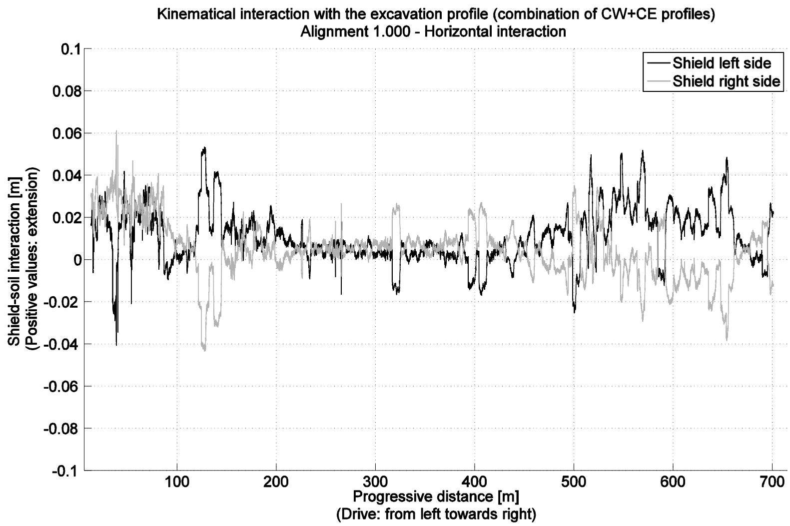

Figure 4: Shield-soil calculated horizontal kinematical interactions; North-South line tunnel – Running tunnel 1/East

5 CONCLUSIONS

Solid numerical analyses of shield-tunnelling in soft soil have to be based, among others, on an improved understanding of the physical processes occurring at the shield-soil interface. The kinematical analysis presented offers an analytical tool in that direction. Comparing the behaviour of an articulated and a non-articulated shield showed that the articulation offers higher stability, with smaller fluctuations on behalf of the interaction displacements. The articulation also enhances to shield's capability to follow the excavated gap, limiting the induced soil displacements. Direct measurements for the validation of the interface displacements as above determined is currently not available. However, two possible alternatives seem viable. First, the subsurface displacements around the tunnel can be monitored during construction and compared with the shield-induced calculated displacements. Second, the calculated interface displacements can be converted into a stress distribution on the shield skin. The integral of the pressures on the entire shield has to balance the TBM driving forces. This second validation option is to be pursued in further research.

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