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Tunnelling in Soft Soil: Tunnel Boring Machine Operation and Soil Response

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ABSTRACT: Constructing tunnels in soft soil with the use of Tunnel Boring Machines may induce settlements including soil movements ahead of the face, soil relaxation into the tail void, possible heave due to grouting, long lasting consolidation processes, and potentially several other mechanisms. A considerable amount of the total soil displacements seems correlated with the passage of the TBM-shield. Even so, the TBM-induced soil displacements have so far only been coarsely correlated to the total settlements. This paper attempts to relate the shield geometry and its operation through the soil with the observed soil displacements. The snake-like motion of the shield within the excavated soil profile is one of the key aspects as the erratic advance of the shield appears to induce unevenly distributed ground displacements at the interface with the soil. These displacements are expected to spread through the soil with a similar pattern. A numerical investigation on the TBM kinematics and the associated soil response has been performed based on the monitoring data from the construction of a tunnel in The Hague, The Netherlands, in order to quantify these aspects. Results confirmed that the geometry and the operation of the TBM-shield through the ground influence the amount and distribution of the induced soil displacements. The analysis also highlighted the essential role that the tail-void grouting has not only in filling-in the tail-void but also in compensating the kinematical effects of shield advance.

Keywords: tunnels, soft-soil, kinematics, displacements, grouting

1 INTRODUCTION

Tunnel Boring Machines (TBMs) are used to construct tunnels in challenging environments (Mair et al. 1996). However, the current soil-settlement predictions are still largely based on the experience gained from previous projects and little correlated with aspects such as the TBM features and its kinematic behaviour. The predictions' accuracy and reliability are therefore negatively affected. The interaction processes between the TBM, the soil, and the process fluids is a critical aspect to be better understood in order to improve the tunnel-boring's reliability.

This study aims to establish a quantitative correlation between the soil displacements observed during the construction of a TBM-driven tunnel and the specific driving pattern of the TBM. Special attention is given to how the TBM-shield interacts with the cavity excavated by the cutting wheel. The study is based on the monitoring-data from the Hubertus Tunnel, a double-tube road tunnel located in The Hague, The Netherlands.

The Hubertus tunnel tubes, northern and southern, are 1666.70 m and 1653.48 m long. The tubes were excavated by a 10 680 mm long slurry-shield TBM, with a front diameter of 10 510 mm, and a rear one of 10 490 mm. A standard radial overcutting of 10 mm was permanently used. The tail-void grouting occurred via the upper four of the six injection openings available. The final lining is formed by 2 m long prefab reinforced-concrete elements, with an external diameter of 10 200 mm. The deepest point of the tunnel axis is located at 27.73 m below surface. The groundwater level may be assumed at +1.0 m above N.A.P. (Dutch Reference System approximately equivalent to the Mean Sea Level). Further details of the Hubertus tunnel project may be found in Festa et al. (2012).

2 SUBSURFACE SOIL DISPLACEMENTS

The subsurface soil displacements were monitored with 4 cross sections equipped with extensometers and 4 equipped with inclinometers. The tunnel advances are reported in Tables 1 and 2. Each monitoring section was equipped with 7 boreholes numbered from 1 to 7 from right to left in direction of drive and where either extensometers or inclinometers were installed. Only 5 of the 7 boreholes were actually instrumented during each passage, chosen as the closest ones to the tunnel being bored. For each cross section, the time span investigated ranged from the moment in which the TBM-face was 25 m before the section, until the face was 50 m after the section. In Figs. 1 and 2. these positions are represented as -25 and +50, respectively. The same holds for Figs. 3 and 4.

Table 1. Position of monitoring sections southern alignment [km]

	Section 1	Section 2	Section 3	Section 4
Ext.	-1+588.16	-1+556.51	-1+149.01	-1+095.42
Incl.	-1+586.59	-1+555.22	-1+147.87	-1+094.20

Table 2. Position of monitoring sections northern alignment [km]

	Section 1	Section 2	Section 3	Section 4
Ext.	-1+600.57	-1+571.24	-1+161.58	-1+108.04
Incl.	-1+599.40	-1+570.15	-1+160.32	-1+106.73

2.1 Extensometers

The vertical movements monitored at the first monitoring section are presented in Figs. 1 and 2. The settlements are expressed in mm. Each graph refers to a single sensor. The initial reference value is assumed when the shield is 25 m before the monitoring section, and data is collected continuously during advance. Vertical lines mark meaningful relative positions of the TBM-shield face with respect to the monitoring section.

Two aspects deserve attention. First, the settlement troughs are non-symmetrical with respect to the tunnel axes. Settlements are higher at the left-hand side than at the right-hand one. Second, a marked recovery of the pre-occurred settlements is observed during the second passage when the shield tail crosses the monitoring section. A similar recovery is not present during the first passage. The heave is more effective close to the tunnel than at distance. Considering the borehole 3 directly above the second tunnel axis, 75% of the pre-occurred settlements are recovered at the depth of the deepest sensor (2 m above the extrados of the tunnel), while only 25% is recovered at surface level.

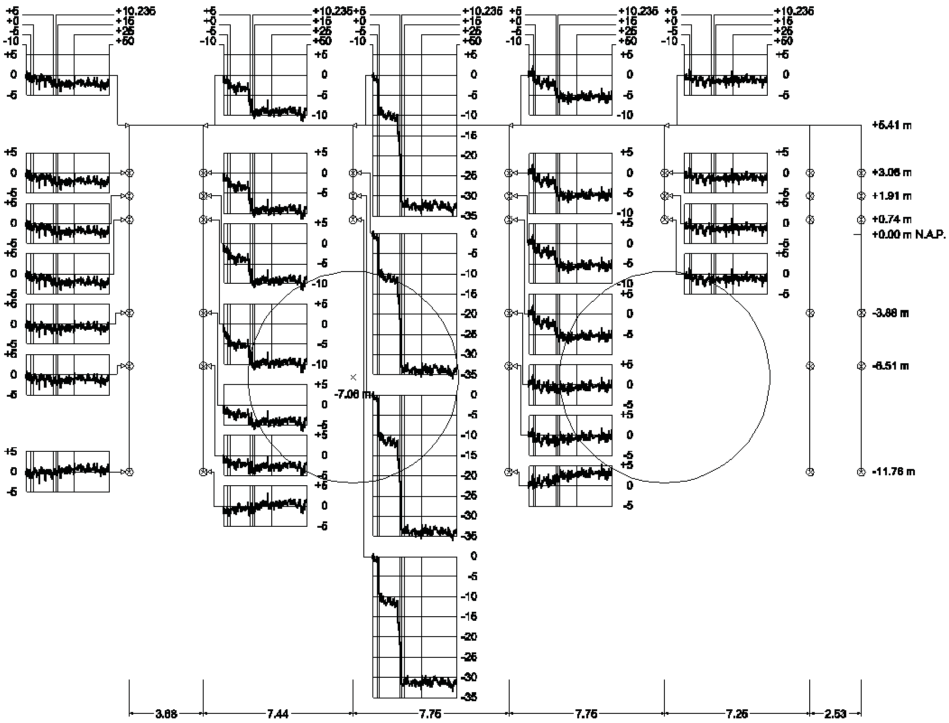

Figure 1. Extensometers at monitoring section 1 - first passage – northern tunnel – 2006 (settlements in mm)

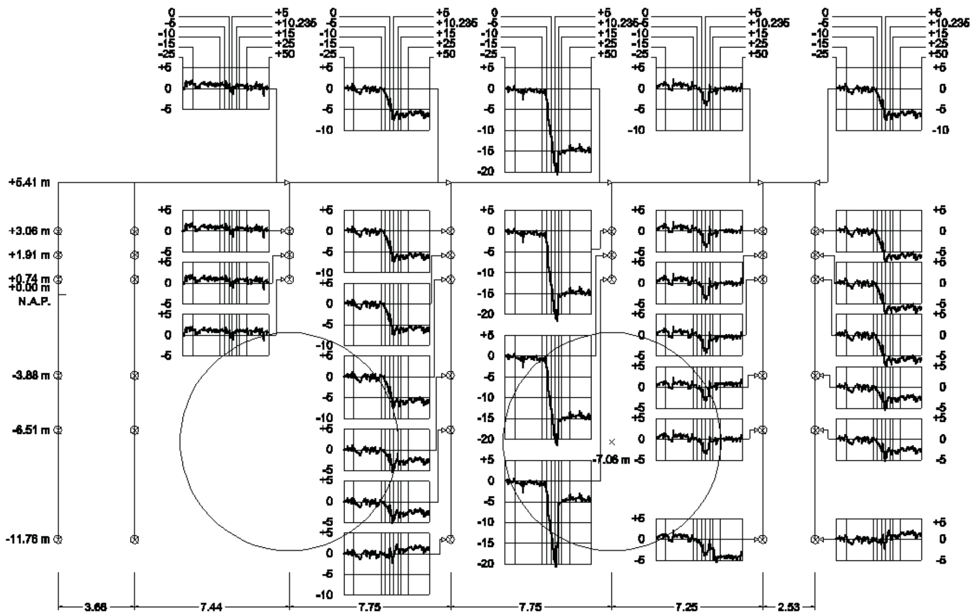

Figure 2. Extensometers at monitoring section 1 – second passage – southern tunnel – 2007 (settlements in mm)

2.2 Inclinometers

The results of the inclinometers' readings are summarized in Figs. 3 and 4. The initial reference value is usually taken when the shield face is 25 m before section 1. The displacements are expressed in mm.

During the first passage, at the left-hand side of the tunnel a converging trend is observed. The maximum convergence, amounting to 17 mm, is observed at the depth of the first sensor in borehole 6. In borehole 7 a horizontal convergence of 8 mm is observed at surface level. Deeper on the same side of the tunnel the observed converging displacements are 10 mm in borehole 6 and 5 mm in borehole 7. At the right-hand side, the horizontal displacements range from -2 mm (convergence) to +2 mm (divergence) in the sector of borehole 4 spanning from the depth of the tunnel top to the tunnel spring-point depth. In the upper sector of the borehole converging behaviour is observed up to 7 mm near surface.

During the second passage, the horizontal displacements diverge at the right-hand side of the tunnel after an initial converging phase peaking when the TBM-face is after the cross section for half of its length. The maximum rightward displacement amounts to 14 mm in borehole 2 and to 12 mm in borehole 1. At the right-hand side the displacements start to diverge markedly from the passage of the shield tail on. The peak is reached when the TBM-face is 25 m after the cross section. At the left-hand side, neither a clear convergence nor a divergence are observed at the depth of the tunnel-axis. Closer to the surface a converging displacement of 5 mm is observed.

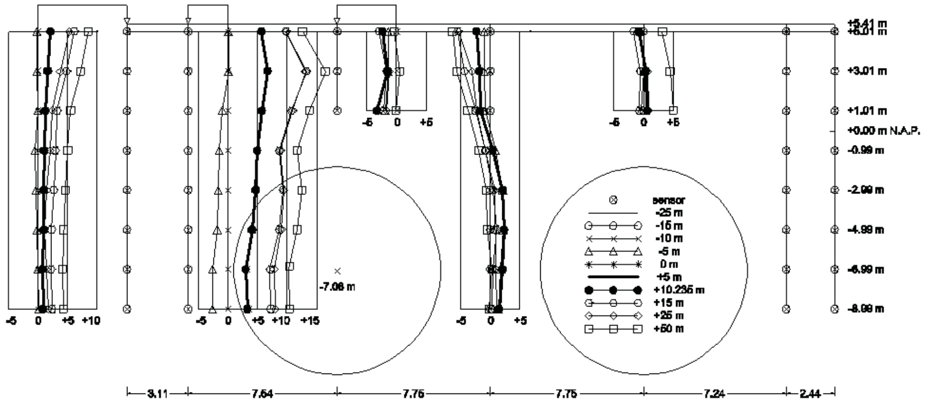

Figure 3. Inclinometers at monitoring section 1 – first passage – 2006 (displacements in mm)

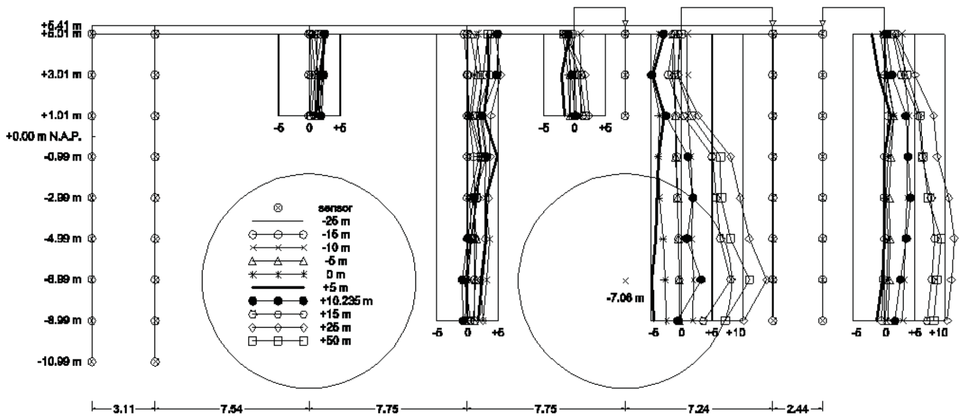

Figure 4. Inclinometers at monitoring section 1 – second passage – 2007 (displacements in mm)

3 TBM-SHIELD AND SOIL KINEMATICAL INTERACTION

The interaction between a TBM-shield and the surrounding soil is quantified by accounting for the relative distance between the shield-skin and the excavated profile. The deviation of the TBM-shield from the planned tunnel alignments was investigated in a previous study by the same authors (Festa et al. 2011). The research method consisted of comparing the actual positions of the shield with the cavity excavated by the cutter head through the soil, in turn obtained as the record of the positions incrementally occupied by the cutter head as the TBM advanced. The comparison allowed to quantify the displacements induced by the advancing shield at the shield-soil interface. Given the well-known snake-like motion of the TBM, it was reasonable to expect the existence of sectors of the shield where the surrounding soil is either compressed or extended. Comparing the relative position of the shield-skin with the excavated profile proved useful in order to demonstrate this behaviour.

4 SOIL DISPLACEMENTS AND TBM'S KINEMATICS

In each of the 8 graphs of Fig. 5 the shield-soil interface displacements are compared to the soil response. The horizontal displacements presented are those occurring at the depth of the tunnel axis. On the x-axis are the shield-soil interaction and the horizontal soil displacements. On the y-axis is the distance of the shield-face from the monitoring section. The shield-soil interaction lines (kin. displ.) represent the amount of displacement induced at the shield-soil interface by the shield tail. For instance, in the first graph, when the TBM face is at the monitoring section (0 on the y-axis), the shield tail is 10.235 m behind, and the value of interaction is represented in correspondence of 0, and not of -10.235.

Horizontally, the soil responds differently between first and second passage even if the shield-soil kinematical interaction is comparable, with an average 40 mm soil extension on the left-hand side and a 20 mm compression on the opposite side. On the left-hand side during the second passage there is no sign of soil extension even in presence of a gap up to 60 mm. On the right-hand side, even if in both cases the shield-tail does not compress the soil when passing through the control section, the soil responds with no divergence during the first passage, while it responds with expansion at the second one. These excludes a deterministic relationship between the interface displacements and the soil response.

Vertically, while during the first passage the settlements progress continuously downward, during the second one a remarkable heave is appreciated. As from Fig. 2, the settlements' recovery is particularly effective close to the tunnel top. The upheaval begins when the tunnel face is between 5 and 10 m after the control section, suggesting that the effect of the tail-void grouting is anticipated compared to the passage of the shield tail right across the control section.

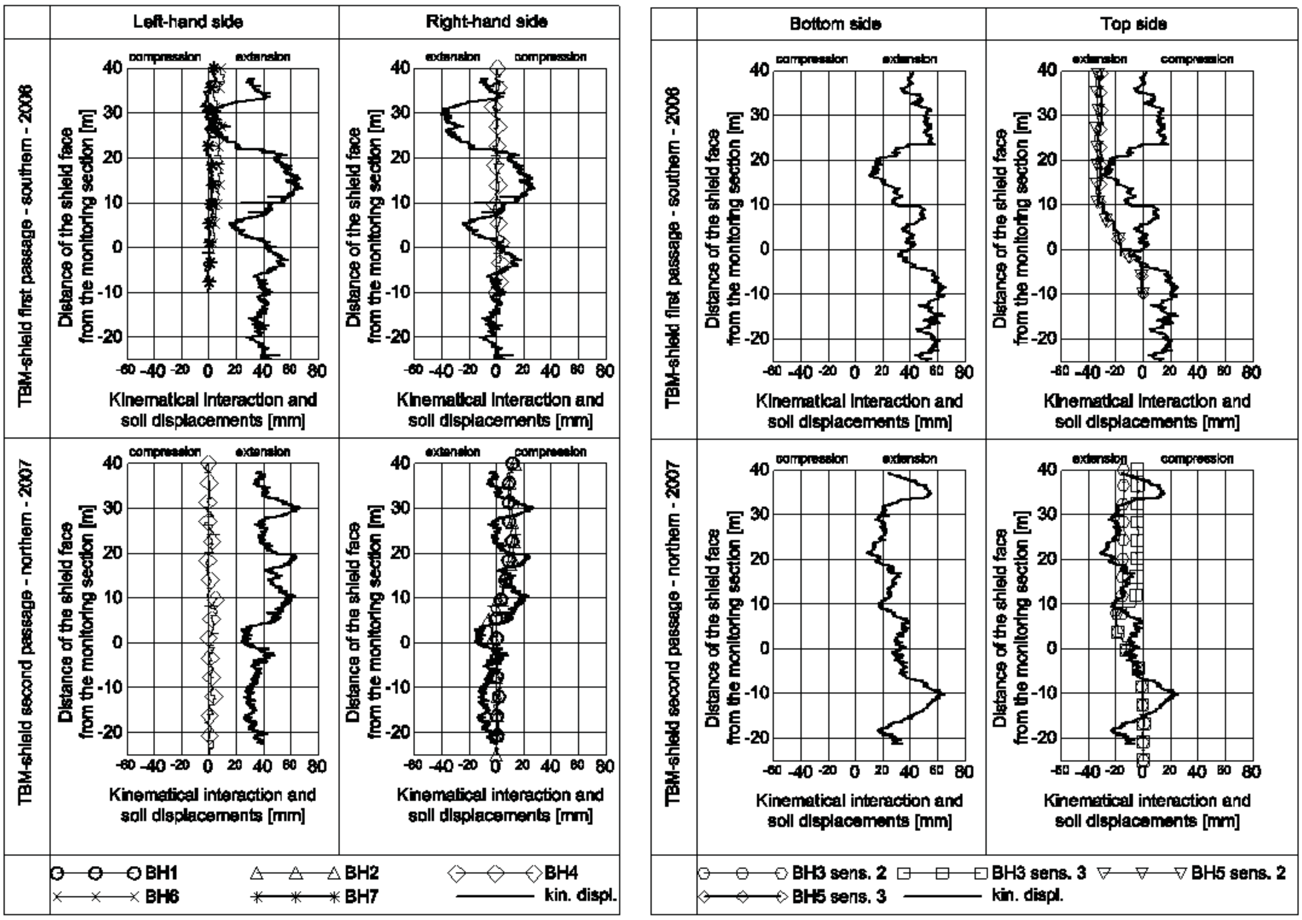

Figure 5. Shield-soil interaction and soil response – cross-section 1

In conclusion it seems that even if the shield-soil kinematical interaction plays a role on the induced soil displacements, an even major role is played by the grouting process. This is suggested by three observations: 1) during the second passage, at the left-hand side the ground does not converge towards the tunnel even in presence of a theoretical void gap of about 60 mm; 2) at the right-hand side, during the second passage the displacements are markedly more expansive than during the first passage, even with comparable shield-soil kinematical interaction; 3) at the top side during the second passage there is no kinematics-related reason to justify such a sharp recovery of the settlements.

5 CONCLUSIONS

Tunnel construction in soft soil usually induces settlement in the surrounding ground even when tunnel boring is performed with a Tunnel Boring Machine (TBM). Most of the current soil-settlement predictions still disregards relevant aspects such as the TBM features and its real kinematic behaviour when driven through the soil. Based on a recent tunnelling project in The Netherlands both TBM and subsurface soil displacements monitoring data were processed in order to compare the TBM-shield kinematic behaviour with the soil response to it. The comparison highlighted the existence of a relationship between the two. However, even more importantly, it appeared that the tail-void grouting process in certain conditions has an essential role not only in filling-in the tail void but also in compensating for the kinematical effects of shield advance. Further research is advisable in two directions. First, the established correlation between TBM-shield kinematics and induced soil displacements has to be generalized to more cases than the single one presented here. Second, the effect of the process fluids on the induced soil displacements in general and of tail-void grouting in particular needs to be addressed more quantitatively.

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