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Tunnel-boring process in urban environment: Modeling for reliability—a kinematic study

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ABSTRACT: Research in tunneling often focuses on the interaction between the TBM and the lining or the TBM and the environment. Little attention has been given to the interaction between the surrounding soil and the grouting process on one hand and the driving characteristics on the other hand. This interaction is influenced by, amongst others, the machine features, the tunnel alignment and the choices of the TBM operators. Although a huge amount of data is automatically collected by the TBM during operations, this data is not directly related to soil properties. A kinematic analysis of the TBM, based on monitoring data of the Hubertus Tunnel is used to show how the interaction between the machine and the surroundings varies from one side to the other of the TBM. This implies that different processes are likely to occur in different positions around the shield. These processes are subject of further study.

1 INTRODUCTION

The increasing use of Tunnel Boring Machines (TBMs) in urban areas, close to historic buildings sensitive to settlements and near to pile foundations, leads to larger technical and operational challenges for these projects.

This has inspired research into the interaction between the TBM, the built up environment and the newly erected lining.

Little attention has been given to the interaction between the soil and the grouting process versus the driving characteristics of the TBM, even though this paper will show that this interaction is significant and can in turn influence the settlements that occur or the extent to which pile foundations are influenced. This paper will present the first results of a research project that aims to improve the understanding and control of the tunneling process in built-up environments.

The overall advancing process of a TBM involves multiple operations and physical processes. Accordingly it has been decided to carry out distinct analyses, investigating the unknown processes one by one, such as to gain a structured knowledge of the overall tunneling process based on a thorough understanding of the separate underlying processes.

Since the kinematic behavior of the TBM appeared of primary interest, this paper will focus on this subject.

1.1 *Reference project*

The kinematic model will be validated by monitoring data collected at the Hubertus Tunnel project in The Hague, The Netherlands. Most of the considerations referred in this paper have therefore been derived from this project, as the full set of monitoring data was available.

2 PRINCIPLES OF GEOMETRY AND KINEMATICS

When a rectangular plane section is driven along a circular path of constant curvature, this motion can be described by a centre of rotation, a curvature and the relative position between the curvature radius and the rectangle.

Different configurations would lead to different descriptions of the motion of the TBM. This is illustrated in the following figures. In Figure 1 the centre

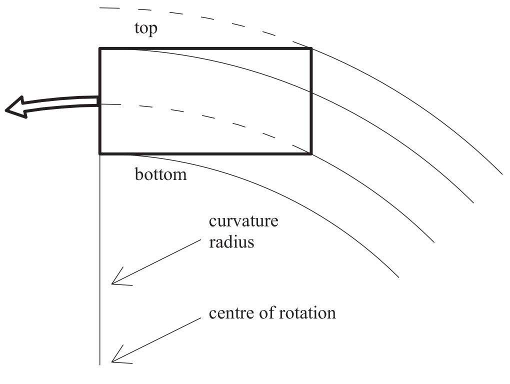

Figure 1. Centre of rotation connected to bottom-left edge.

of rotation is connected to the bottom-left corner of the rectangle; in Figure 2 to the bottom-right.

In both cases the size of the rectangle, the curvature of the trajectory and the angle between the radius and the longitudinal axis of the rectangle (assumed perpendicular to each other, in this example) are the same.

When we focus on the interaction between the top side of the rectangle and the trajectories drawn by its top edges, the first set-up (Fig. 1) shows that the trajectory of the top-left corner is internal to that of the top-right one, while the second set-up (Fig. 2) shows a reversed situation.

This means that, whilst a pure rotation takes place, in the first case the top side must "displace" the surrounding soil, whilst in the second case the surrounding soil can relax after the TBM has passed (assuming any kind of elastic soil behavior).

Finally, an intermediate configuration (Fig. 3) having the centre of rotation connected to the mid point of the bottom side leads to a mixed behavior where at the top side first a phase of relaxation (from the top-left edge to the mid point) and then a recompression (from the mid point to the top-right edge) of the pre-relaxed surrounding soil occurs.

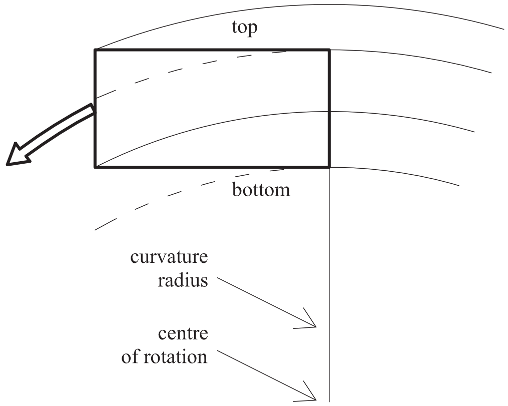

Figure 2. Centre of rotation connected to bottom-right edge.

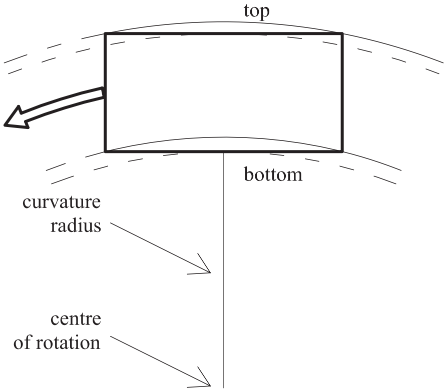

Figure 3. Centre of rotation connected to bottom-centre.

On the bottom side first a phase of compression (from the bottom-left edge to the mid point) and then a phase of relaxation (from the mid point to the bottom-right edge) occur.

Also notice that in this last configuration the trajectories of the top and bottom edges are superimposed.

The configuration depicted in Figure 3 seems most likely and adheres closely to general expectation of how a TBM behaves.

The exactness of this description will be discussed in Paragraph 3, when a comparison with monitoring data is made. However, the three different configurations show that the method of steering and the centre of rotation of the TBM do strongly influence the interaction with the surrounding soil, as well as the forces and moments acting on the machine.

2.1 *Shield positioning systems*

The positioning and guidance system of a TBM is provided through a series of measuring devices and reference points installed both inside the shield and along the concrete lining already in place.

A laser receiving box is connected to the shield and located in the upper part of it, around halfway of the shield length. The receiver is equipped with two target plates to determine the jaw of the TBM and two inclinometers to determine its roll and pitch.

These devices provide the position of the machine and its orientation in space.

Information is collected and recorded at a variable time interval, usually 5–6 seconds long.

The driving system is based on two imaginary (calculated) points inside the shield which follow the designed tunnel alignment. Both lay along the longitudinal axis of the shield: the first one (front) is positioned at the front face of the shield and the second one (rear) at an intermediate position between the front and the rear section, and generally does not coincide with the rear section.

Following Figure 4 provides a plot of the scheme described.

The overall purpose of the monitoring system is to provide to the TBM operators information on the actual position of the two (calculated) points versus their optimal position corresponding to each advance of the machine. Other derived values are also provided (e.g. tendencies, pitch, roll, jaw).

Comparing this steering system with the three configurations assumed in the previous section we

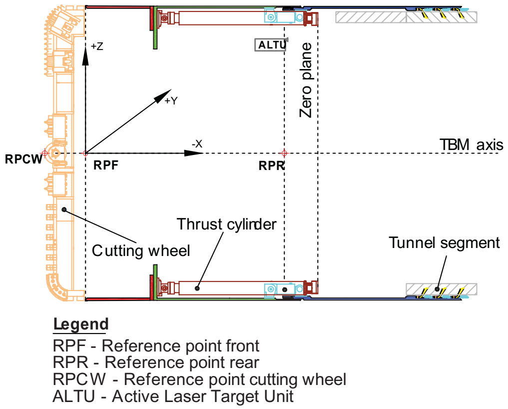

Figure 4. Shield positioning system.

notice that the real situation is actually intermediate between the first (Fig. 1) and the third (Fig. 3).

Therefore peculiarities of both schemes may appear. Cycles of compression and relaxation around the shield occur, as two points on the machine axis follow the same trajectory. Furthermore sideslip of the machine tail can be expected as the second reference point is positioned ahead of the machine tail.

In addition, although machine drivers constantly strive to follow the design alignment with both target points, sometimes this is not possible as this would require excessive driving forces, paired with the risk to damage the equipment and the already placed concrete lining. In those cases it is preferable to keep a slightly skewed orientation of the machine when this involves smaller driving forces. From time to time the skewing required differs in direction and amount.

The understanding and modeling of these driving configurations may also be considered the goal of the present research.

2.2 *Monitored data and models*

All models and matching results presented in this paper are strictly derived from the monitored data. Only a necessary filtering activity has been carried out wherever needed and in case of unlikely physical configurations.

During the modeling phase the interpretation of data and results has been strictly avoided such as to escape from any conditioning to the model.

3 THE HUBERTUS TUNNEL

3.1 *Main features*

The Hubertus Tunnel consists of two parallel tubes long 1666.70 m and 1653.48 m. The Hydroshield is 10,235 mm long, at front has diameter of the shield of 10,510 mm and at rear of 10,490 mm, i.e. the shield has a tapering of 10 mm (in radius). Furthermore a standard overcutting of 10 mm (in radius) is present.

The machine tail void grouting system consists of six injection openings distributed along the circumference. Of these only four (the upper ones) were used during the operations.

The final concrete lining is made from 2000 mm long rings with an external diameter of 10,200 mm. The theoretical tail void thickness is therefore 165 mm.

Figure 5 shows an overview of the design alignment, with the smallest horizontal curvature radius of 550 m. The deepest point of the tunnel axis is located at 27.73 m below surface. The tunnel is located in dune sand consisting of well packed silty sands and sandy silts with some clay.

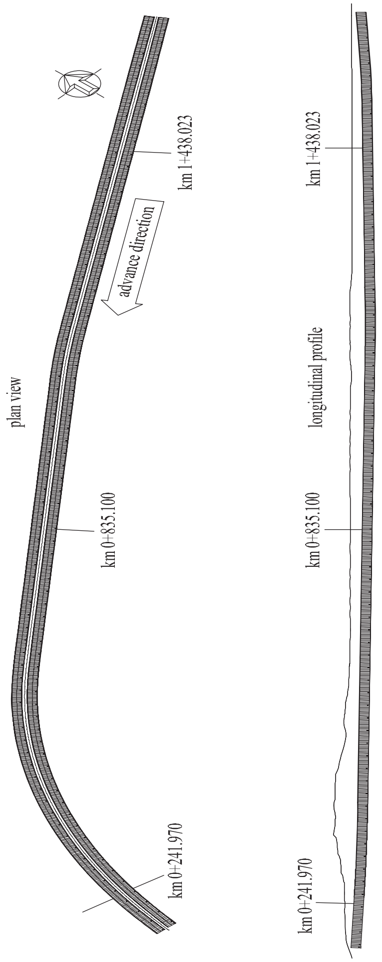

Figure 5. Hubertustunnel project: designed alignments.

4 THE KINEMATIC MODEL

4.1 *Motivation*

The kinematic behavior of the TBM was selected as the first sub-process to study as this is of direct interest to the TBM operators (as it is common to follow the design alignment with the least diversion possible).

A kinematic model could help to understand unpredictable reactions of the TBM encountered especially during the initial phase of the boring operations and could be used to improve operational control of the TBM.

The kinematic model can also be considered the first step towards a full model predicting changes in the stress distribution around the tunnel and anticipating strains and settlements.

Such a model, including processes such as grouting and the interaction with surrounding soil, is the desired result of the full research program.

4.2 *Development*

The advancement of the shield has been measured and recorded for both tubes.

This has been reported as the horizontal and vertical deviations from the theoretical alignment of the front and back target plates of the positioning system.

As the average time interval between two measurements is around 5 to 6 seconds, the advance between two adjacent readings is in the order of few mm.

According to the monitored advance, taking into account the deviations from the optimal aligning, the tracks of the excavation wheel and of the shield tail have been calculated with the use of MATLAB.

At this stage of the research the shield tail has been assumed non-deformable. This condition, more or less realistic according to soil conditions and shield features, will be reconsidered in the future.

The resulting model allows displaying the TBM shield in any advance position along the alignment. In addition, thorough the comparison of the shield skin with the mentioned tracks, the amount of interaction of the TBM with soil, in distinct positions around the shield, is visualized.

4.3 *Results*

Some specific results from the model will be discussed.

The first section of interest is encountered at km 1 + 438.023 of the south tube, where the shield is located in a straight downward position. Here the analysis shows where at that location the profile of the shield was inside the track of the excavation wheel or (partially) skewed outside.

Taking two cross sections of the shield, one horizontal and one vertical, we can visualize the amount of compression or relaxation and the amount of interaction at the left, top, right and bottom sides of the shield as shown in Figure 6.

The sign convention is as follows: the gap with a distance between track and shield skin is positive when the shield moves inside the track of the excavation wheel and negative when outside.

If the gap is positive we assume the soil around the shield is relaxed, when it is negative, we assume the shield skin is displacing the surrounding soil.

From Figure 6 one can observe that the shield was driving horizontally skewed towards the right hand side, since the gap on the left side was of 45 mm, whilst on the right side a negative gap (soil displaced), although very limited, was present.

From the vertical point of view, the machine presents a downward pitch (vertical skewing) more emphasized than required by the downward trend of the trajectory (1% in this position). Therefore the machine shows here what we could refer as a sinking tendency in its front part, and a buoyant tendency in its rear section. At the bottom-side the shield tail has a gap width of 60 mm and the soil is relaxed, while the top-side has a negative gap width of 23 mm and the soil is displaced.

Another section of interest is encountered at km 0 + 835.100 of the south tube, where the shield is located in a straight upward position (0.8%).

From Figure 7 one can observe that the shield was driving horizontally straight (left and right side lines are almost superimposed, and the gap at the tail almost coincides with the standard one of 20 mm, obtainable combining overcut and tapering effects), but with an upward pitch (vertical skewing) more emphasized than required by the upward trend of the trajectory. At the bottom-side the shield tail has

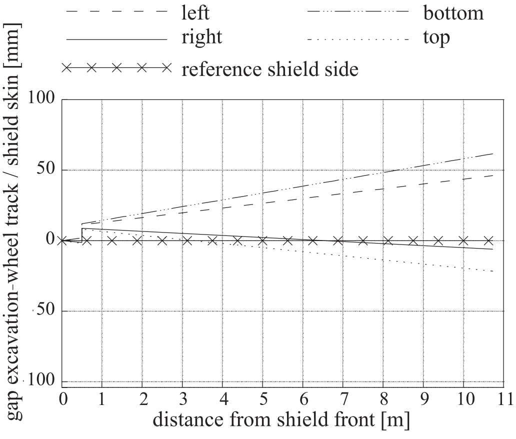

Figure 6. South tube—km 1 + 438.023.

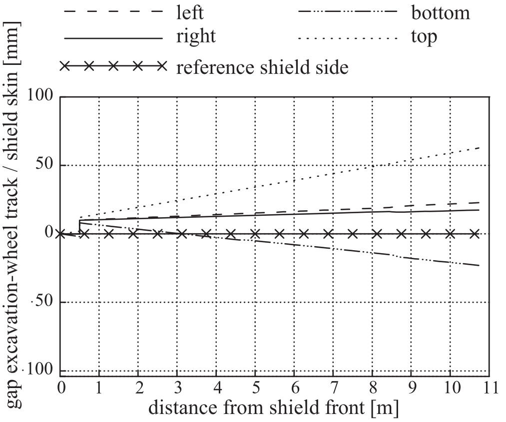

Figure 7. South tube—km 0 + 835.100.

therefore a negative gap width of 25 mm and the soil is displaced, while the top-side has a positive gap width of 60 mm and the soil is relaxed.

It is interesting to compare this last case to that shown in Figure 6. Focusing on the vertical behavior of the shield, we observe a reversed situation between top and bottom sides in the two cases, both from the qualitative (sign of the gap) and quantitative (width of gaps) point of view.

In other words the shield seems to emphasize the vertical trend of the trajectory both when in downward and upward direction.

At km 0 + 241.970, where the trajectory has a horizontal curvature radius of 550.00 m (leftward) and an upward steepness of about 4%, the shield shows a gap width on the right hand side of 20 mm (Fig. 8). The complementary effect can be seen at the left hand side where the tail gap thickness is 50 mm, therefore larger than the standard one of 20 mm (when combining the overcut and tapering effects).

From the vertical point of view the shield has a negative gap width of 70 mm at the top side, with a positive gap width increasing to 110 mm at the bottom side (Fig. 7).

The curved trends of the left and right side lines deserve additional explanations.

In contrast to the two previous cases, the TBM is in a horizontal leftward curve. Therefore the track of the excavation wheel is also curved.

As depicted in Figure 3, at the top side, the gap goes from zero at the front, to a maximum in the mid section, and then comes back to zero at the tail. If we assume for the top-right edge to protrude outside the track of the excavation wheel, also a zone of compression can be expected, depicted by a negative tail in the line representing the gap width at the right side of the shield. This behavior can clearly be seen in the “right” line of Figure 8.

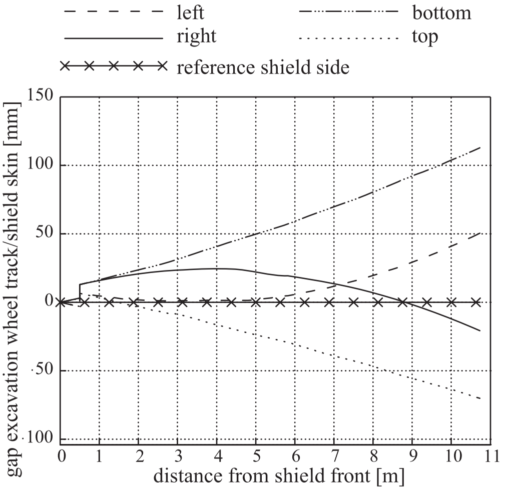

Figure 8. South tube—km 0 + 241.970.

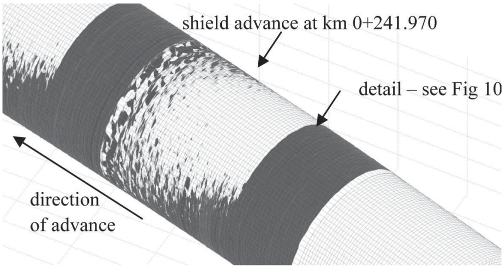

Figure 9. 3D view of the shield at km 0 + 241.970.

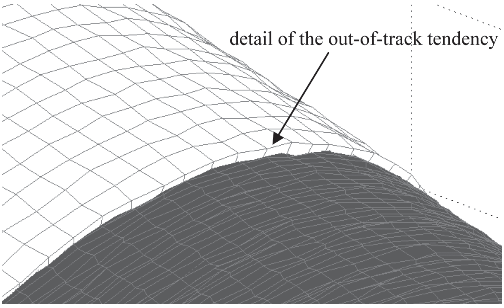

Figure 10. Detail of the out-of-track at the top side at km 0 + 241.970.

The theoretical size of the gap width at the top side (negative in this case, therefore with displaced soil) is also visualized in Figures 9 and 10, as a 3D model.

The shield skin is depicted in white, the track of the excavation wheel in grey. Where white is visible, this means that the shield skin is out-of-track in that sector and displaces the soil outwards.

This happens anytime the shield-tail protrudes outside the tube excavated by the excavation wheel.

5 CONCLUSIONS

5.1 *Summary and highlights*

The results of a kinematic analysis carried out on the monitoring data obtained at the Hubertus Tunnel project in The Netherlands have been presented.

The study of the kinematic behavior of a TBM shield is the first step towards the construction of a full numerical model predicting changes in the stress distribution around the tunnel.

Results show that also in standard driving conditions, the interaction of the shield with its surrounding and the extent to which soil is displaced or relaxed can significantly change from one side to the other of the TBM. This means that different physical processes (e.g. soil compression/relaxation, grout flow around the shield, shield-tail deformation) are likely to occur in distinct positions around the shield, therefore influencing its own equilibrium.

At this stage the shield tail has been simplified as non deformable.

A more complete set of results, broader than the selection presented in this paper, shows that in different positions along the alignment, although with similar curvature and steepness, the behavior of the shield differs. A number of factors can contribute to this effect, including varied soil conditions and varied maneuvering.

More research is still needed to understand and model how a certain TBM behavior is determined by a specific set of environmental and operational circumstances.

5.2 *Forthcoming research*

A next step would be to take the gap width derived with the present model into account in an analysis of the tail void grouting process.

From the model presented, it is possible to retrieve the size of the gap created by the advancement of the shield and its spatial distribution around the TBM. This could be used to establish a correlation between the *theoretical grouting need*, and the amounts of grout actually injected during the boring process.

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