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An investigation into the forces acting on a TBM during driving – Mining the TBM logged data

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ABSTRACT

The state-of-the-art of tunnelling in difficult ground conditions and built-up areas still involves a trial-and-error approach as a complete understanding of the physics governing the interaction between TBM and surrounding soil is still lacking. This paper makes a first attempt to quantifying the driving forces applied to a slurry-shield TBM in sand, together with their spatial and temporal distribution, in order to obtain a better understanding of the TBM–soil interaction process. The monitoring-data of the Hubertus Tunnel in The Hague, The Netherlands, was used, and results show the soil reaction on the TBM needed to equilibrate the system of forces and moments acting on the TBM. This result is validated by the kinematic behaviour of the TBM that has been derived from monitoring as well.

1. Introduction

Tunnel Boring Machines (TBMs) are more and more used to construct tunnels in challenging environments, such as built-up areas. As a construction technique, it has widely proven to be effective and socially acceptable (Lance and Anderson, 2006). Nevertheless, clients are setting increasingly stricter standards on design engineers, TBM manufacturers, and operators. Therefore, predictive risk analyses come into play, as most of the political and technical decisions are based on these. In particular in the design stage, risk analyses are used to predict how the tunnel construction will affect its surroundings. However, predictions are still largely based on the experience gained from previous projects, therefore often lacking in adequate case-specificity (Mair and Taylor, 1997). In other words, the expected level of risk is defined through worst scenario figures, usually expressed in terms of a 'volume loss' rate, obtained from the records of previous tunnels bored in similar circumstances. The 'volume loss' is then processed via empirical (Peck, 1969), analytical (Verruijt, 1997), or numerical analyses (Komiya et al., 1999; Sugimoto and Sramoon, 2002; Sugimoto et al., 2007; Nagel, 2009), such as to derive the expected absolute and differential settlements of the surrounding soil and constructions. Finally, based on criteria of acceptable damage (Mair, 2011), it is judged whether the project is technically feasible and socially acceptable. However, according to this 'conventional' approach, settlements predictions are hardly correlated with project-specific features, such as the TBM specifications and its real kinematic behaviour when driven through the soil. Consequently, the predictions' accuracy and their reliability risk to be negatively affected. In this context, the interaction processes between the TBM, the soil, and the process fluids certainly represent a critical aspect. Their better understanding can improve the reliability of the overall tunnel boring process.

The disregard concerning the TBM features and its operation is surprising, particularly considering that observed longitudinal settlement profiles show the remarkable effect of the TBM–shield transit on the overall induced surface settlements, as also shown by the interaction models between the TBM–shield and the surrounding soil by Sugimoto and Sramoon (2002), Kasper and Meschke (2006), and Nagel et al. (2010). These models approach the tunnel-construction problem theoretically, aiming to find adequate validation from real cases at a later stage. In this research an opposite approach is proposed, namely to investigate the system of forces and pressures applied to drive a slurry-shield TBM. The study is based on the monitoring-data collected during the construction of the Hubertus Tunnel, a double-tube road tunnel located in The Hague, The Netherlands. This tunnel, excavated between 2006 and 2007, was selected for two reasons: first, the combined availability of TBM and soil-displacement monitoring data, and second, thanks to its recent completion, the accurate feedback obtainable from people involved in the project.

The Hubertus Tunnel consists of two parallel tubes, north and south, 1666.70 m and 1653.48 m long, respectively. The tubes were excavated by a non-articulated 10,680 mm long Herrenknecht slurry-shield TBM, with a front diameter of 10,510 mm, and a rear one of 10,490 mm (i.e. with a radial tapering of 10 mm). A standard

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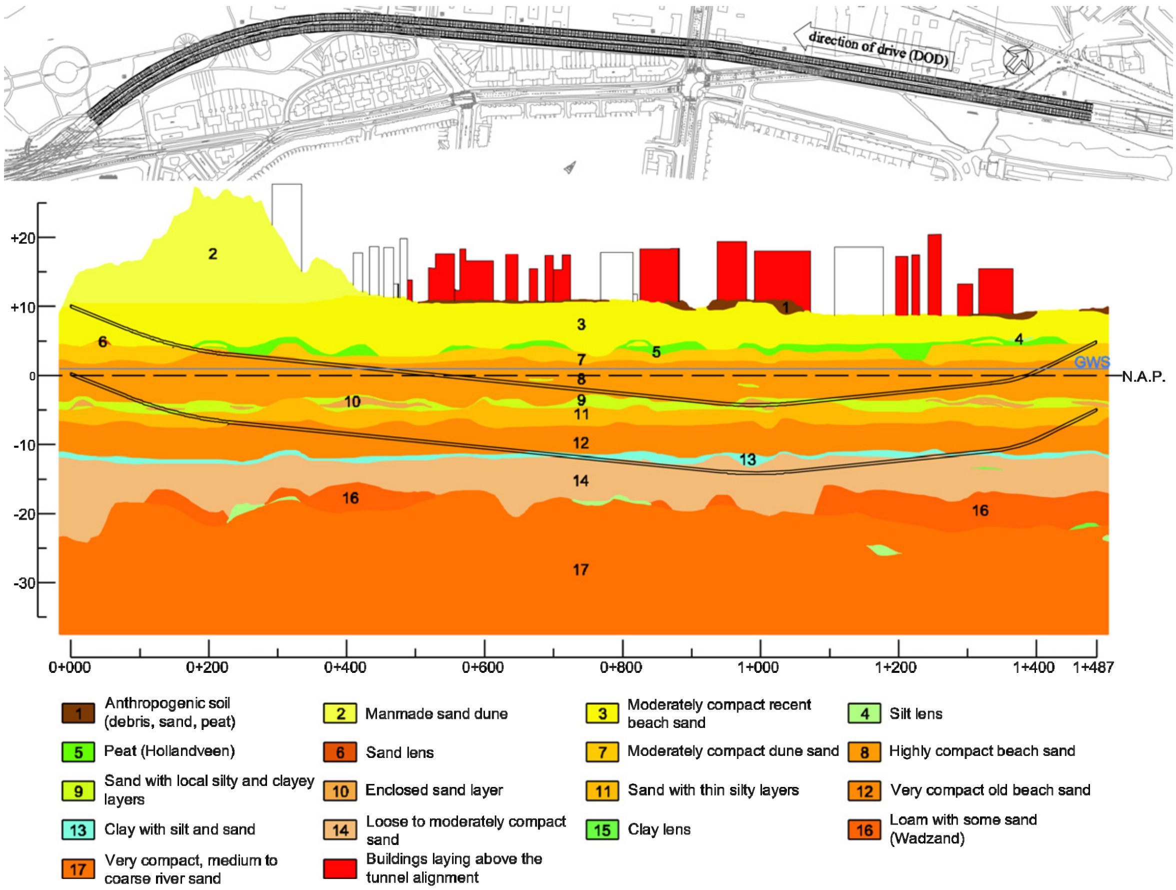

Fig. 1. Hubertus Tunnel: Geological profile and plan view.

radial overcutting of 10 mm was permanently used. The cutting wheel was supported by a longitudinally displaceable spherical bearing, and handled via three couples of hydraulic cylinders. The tail-void grouting occurred via the upper four of the six injection openings distributed along the shield tail. The final lining is formed by 2 m long prefab reinforced-concrete elements, with an external diameter of 10,200 mm. The theoretical tail-void gap is 145 mm. The sharpest horizontal curve with a curvature radius of 542.3 m, is located in the south alignment, and was bored in leftward direction. The deepest point of the tunnel axis is located at 27.73 m below surface. The groundwater level may be assumed with sufficient accuracy at +1.0 m above N.A.P. (Dutch Reference System) (see Fig. 1).

2. The data analysis

The practice of controlling the TBM driving parameters is well established for construction purposes, and for that aim the data is often subject to time-based averaging. This research instead mines the complete series of recorded data, and investigates how these can contribute to an improved understanding of the interaction between the TBM and the surrounding soil. In the present paper a selection of data from the south alignment will be analysed.

The analyses and results presented are the second step of a wider research effort aimed to clarify the TBM–soil interaction problem. The first step has quantified the interface-displacements occurred between the excavated soil profile and the shield-body, which was obtained by a kinematical analysis of the TBM–shield behaviour (Festa et al., 2011a,b). In the upcoming stage, the displacements-field derived at step one will be transformed into a stress-distribution at the shield–soil interface. Finally, in the fourth stage, the equilibrium between the applied forces and pressures (active system) and the soil reaction (passive system) will be determined. The last two research steps mentioned are not presented here.

Operating a TBM involves a complex sequence of operations requiring knowledge and control. Knowledge represents the possibility for the machine drivers to know as many as possible of the parameters concerning the status of the machine. Control stands for the opportunity they have to modify some driving conditions (i.e. forces, pressures, speeds). These two aspects are interconnected in an iterative manner via the TBM Information and Control System (here TBM-ICS).

2.1. The structure of the TBM logged-data

The TBM-ICS logs all the information concerning the TBM status and the construction process. This data can be grouped as: positioning, hydraulic pressures, fluids handling, status bits, currents, and voltages. Only hydraulic pressures, fluids handling, and status bits will be considered in this paper, in order to describe the system of forces and pressures acting on the TBM. The positioning data were used instead to build the kinematic model described in Festa et al. (2011a,b).

Data acquisition is a time-based continuous process. Each time step the signals from all the sensors are sequentially acquired and recorded. The time step between two subsequent acquisitions varied between 5 and 6 s, and the data set were separated into individual files for each separate ring, with a new file created at the start of ring excavation. The shield advance is calculated based on the positioning data. However, the shield advance is not strictly increasing in time, since standstills, small position fluctuations, and measurement accuracy can lead to a still, or even backward