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TBM soft ground interaction: Experimental study on a 1 g reduced-scale EPBS model

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ABSTRACT

This paper brings new elements of understanding on the stress–strain behaviour of soils during tunnel excavation using earth pressure balance shields (EPBS), thanks to laboratory tests carried out with an original reduced-scale physical model. Typical experiment results obtained during tunnelling with different soil types (purely frictional, cohesive-frictional) and different geometries (homogeneous or stratified grounds) are presented and discussed. These results mainly concern the soil stress–strain behaviour around the tunnel boring machine (TBM) and the soil-machine interaction at ideal rates of excavation. Firstly, results concerning the identification of pertinent control parameters to guarantee the safe advancement of the machine and the ground-supporting function of the cutting wheel are analysed. Surface settlements, stresses and displacements around the tunnel and behind the tunnel face, as well as arching effects around the shield are then presented and discussed.

1. Introduction

Due to traffic congestion and environmental factors, urban development nowadays involves the construction of new tunnels, either small-diameter for underground networks (water supply, sewerage, electric power lines, telecommunication) or large-diameter for transportation purposes (railways, roadways). The increasing popularity of underground space is consequently the source of the growing complexity of underground structures to be built. In soft grounds, especially in urban areas, control of soil deformation during excavation is the predominant problem. Indeed, a stringent control of surface settlements and displacements near the tunnel is essential to preserving a dense and vulnerable housing area at ground surface, as well as existing underground constructions nearby.

In this context, the earth pressure balance shield (EPBS) method is increasingly used for many tunnelling projects in the urban environment, both for efficient tunnelling operations and the minimization of ground volume loss – the latter being vital for ground movement reduction and control. The fundamental idea of this method, which originally arose in Japan in the seventies (Kurosawa, 1981), consists of balancing the hydrodynamic and earth pressures at the tunnel face by a controlled confinement of the excavated soil contained in the working chamber at the front of the shield. Initially, this method was mainly used in low-permeable soils (less than about 10^{-4} m/s) but advances in technology, for example the use of additives in the working chamber, have allowed its use in increasingly varied contexts.

In theory, a steady excavation rate requires that the amount of material contained in the working chamber remain constant. This condition is obtained when the mass of soil extracted from the working chamber by the screw conveyor remains equal to that of the excavated soil entering the chamber. However, experience shows that this balance is quite difficult to achieve on site. The standard strategy concerning ground control in TBM tunnelling is most often based on weighing the extracted materials. This approach may however fail to detect over-excavation and under-excavation situations with reasonable reliability and sufficiently early on, because the conversion of weights to excavated volumes involves appreciable uncertainty. The definition of additional control parameters (like ground pressures in the working chamber, thrust effort and torque on the cutter head, …) therefore appears essential if the safe driving of the machine is to be guaranteed.

In practice, any deviation from this ideal balance is not the only source of volume loss. Deformations of the soils occur in front, above and behind the TBM during its advancement, and the total volume loss is caused by the combined effects of the frontal extrusion and the radial convergence of the excavated ground. The frontal displacements are generally due to a default of the support pressure at the tunnel face which can be induced by a deviation from the ideally balanced conditions described above. Indeed, this face pressure is provided partly by the thrust from the cutter head and partly by the pressure of the excavated ground contained in the chamber. In parallel, the radial

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displacements of the ground above and behind the TBM are mainly induced by the presence of an annular void between the shield and the surrounding ground related to the overcutting and the taper of the shield. The deformations of the soil within this gap depend on several factors like the geometry of the machine, the characteristics of the ground, the deformation of the TBM, the presence of bentonite injection around the shield, the pressure of the grouting injection between the extrados of the lining and the excavated ground.

The Laboratory of Civil Engineering and Building Sciences at the ENTPE in Lyon (France) started a large research project several years ago, in collaboration with the "Centre for Tunnel Studies (CETU)". This project is focused on tunnel excavation using EPBS. The project aims to understand the physical phenomena occurring during tunnelling operations and TBM advancement, especially the soil/machine interaction, and to enhance the performance of numerical modelling of ground movements due to mechanized tunnelling in soft ground.

The approach used is based on laboratory tests carried out with an original reduced-scale physical model of an EPBS. This physical model, with a geometric scale between 1/4 and 1/20 in reference to the diameter of the machine, allows a realistic simulation of the principal tunnelling operations of a real EPBS: ground excavation with a cutting wheel, confinement of the tunnel face with the excavated material, extraction of the excavated material with a screw conveyor and immediate radial support of the ground by means of a cylindrical shield tail. Note that the installation of the lining and the injection of the annular void are not simulated on this physical model. An extensive instrumentation allows the acquisition of a set of substantial and consistent data of different field quantities, both on the EPBS and on the soil mass. On the one hand, physical mechanisms observed and measurements made in the laboratory are analysed at the model scale and then compared to in situ data. In parallel and based on these experimental observations, analytical and numerical modelling are developed with the aim of providing predictive calculation tools of tunnel face stability and ground movements due to the mechanized tunnelling process.

This paper begins with a brief literature review of physical modelling of pressurized-shield tunnelling. The physical model of ENTPE and its instrumentation are then described in detail. Typical results obtained during fourteen excavation tests carried out with the TBM model in different types of soil mass models (homogeneous purely frictional soils, homogeneous cohesive-frictional soils, stratified soils) are then presented and analysed. Firstly, this analysis concerns the TBM: relevant machine parameters able to guarantee the safe advancement of the TBM are identified and the role of the cutting wheel (in particular its ground-supporting function) is discussed in connection with common practice. The stress–strain soil behaviour around the TBM (in particular soil displacements at the ground surface and in the soil mass, and the arching effect around the TBM) is then analysed. This analysis is performed in the case of ideal tunnelling rates for which the tunnel face stability is ensured and the deformations within the ground around the TBM are limited. Note that the problem of face stability encountered during extreme tunnelling rates (under-excavation or over-excavation rates) is not considered here. An analysis of this problem can be found in Berthoz et al. (2012) where experiment results obtained on the ENTPE's TBM model were confronted with existing theoretical models available in the literature.

2. Previous research using physical models

The specific problem posed by the excavation of tunnels in soft ground (stability of the opening during driving, design of the supporting structures, impacts of works on the environment) has been widely considered in the past. From a theoretical point of view, two aspects are generally considered: analysis of the stability of the structure and displacement calculations. The works on stability analysis are primarily based on the principles of ultimate strength design and essentially concern the behaviour of the tunnel face; in particular the description of the failure mechanisms and the determination of the retaining pressure to be used when the ground itself is not stable. As for displacement calculations, they are frequently used to estimate the stresses applied to tunnel supports and the surface settlements that may occur in particular in the case of shallow tunnels.

The development and the validation of theoretical models in these two domains require necessary data from instrumented sites or laboratory experiments. The first are generally rare in the written form and often incomplete and/or inconsistent. For pressurized shield tunnelling in particular, it is often exceptional to have both soil displacement measurements and detailed descriptions of tunnelling conditions. Such information is however essential when analysing soil stress–strain behaviour around the machine. Among the more comprehensive and consistent data from tunnels excavated by the EPBS method, the works of Clough et al (1983) and Lee et al (1999) are often cited.

Data from laboratory experiments are on the other hand numerous (Meguid et al, 2008). These experiments under normal gravity or centrifuged conditions present the advantage of a good control of the soil's mechanical properties and boundary conditions. They also allow the behaviour of the tunnel and surrounding soil mass to be explored, from a state of initial equilibrium up to failure if desired. However, they are subject to certain limitations that should be taken into account when analysing the results. These limitations include the incapacity to comply with the real state of stress in the case of tests under normal gravity, possible presence of scale effects or edge effects, use of two-dimensional models (plane strain) to represent a three-dimensional problem…

These laboratory experiments to model tunnelling in soft ground can be divided into three categories (excluding the "trap door" systems essentially adapted to highlighting the arching effects around a cavity):

(1) Studies which use plane strain (2D) models and focus their analysis on soil displacements around a transverse section of the tunnel. For these studies performed under normal gravity or centrifuged conditions, the tunnel is generally supported by a flexible sleeve under pressure. Soil excavation is simulated by reduction of the internal pressure applying on the tunnel wall. The works of Atkinson and Potts (1977), Hagiwara et al (1999), Wu and Lee (2003) and Lee et al (2006) belong to this category, for example. In some special cases, the convergence of the tunnel walls is induced by using a more sophisticated device to vary the diameter of the cavity (Lee and Yoo, 2006). In most cases, the soil mass studied is homogeneous and purely frictional (dry sand or metal rollers), cohesive-frictional (wet sand) or purely cohesive (over-consolidated clay). Note that some models of this type have also been applied to layered soils (Hagiwara et al, 1999). In these studies, quantitative analyses were focused on the influence of the radial pressure and volume losses around the tunnel on the magnitude of the surface settlements. The thickness of the overburden is often taken into account. Some such studies have been devoted to the analysis of the impact of tunnelling on surrounding structures (Loganathan et al, 2000; Jacobsz et al., 2004; Lee and Chiang, 2007) or to the stresses in the lining of tunnels in layered soils (Zhang et al, 2015).

(2) Studies which consider a three-dimensional model, whilst being limited to quasi-static loading of the face by an inflatable membrane or a movable rigid wall. In these studies, the radial support of the tunnel is generally performed with a rigid steel tube. Note for example the works of Mair (1979), Chambon and Corté (1991), Sterpi et al (1996), Kamata and Masimo (2003) and Messerli et al (2010) in this category. These models can be used to study the limit face pressure and the kinematics of face failures but they do not allow a realistic reproduction of the TBM advancement process in the ground, and more particularly the stationary behaviour of soil/machine interaction during the ideal tunnelling rate.

(3) Studies that model the progression of the TBM in the ground by