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# Development of a 3D finite element model for shield EPB tunnelling

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ABSTRACT

The paper describes the main features and presents the results of a 3D finite element model for shield EPB tunnelling based on the FE code Simulia ABAQUS. The model simulates important components of the mechanised excavation process including variable muck pressure on the excavation face, cutterhead overcut, shield conicity, installation of jointed segmental lining, annular gap grouting and time-dependent setting of the grout. Advanced numerical techniques are used to model the shield - ground interface, time dependent grout setting and the configuration and stiffness of the segmental lining joints. Three lining models are investigated and compared: continuous shell without joints, shell with aligned joints (2D joint configuration) and shell with staggered (rotated) joints, which is the most realistic 3D lining model.

The results of the numerical analyses highlight the importance of modelling the above features on ground deformations and internal forces of the lining. It is shown that: (1) even moderate face pressure can appreciably reduce ground loss and prevent potential face instability in very weak ground, (2) cutterhead overcut and shield conicity have a pronounced effect of ground surface settlement which can be partly compensated by increasing the grout pressure during tail grouting and (3) a continuous shell model is a reasonable approximation of segmental lining for shallow tunnels.

## 1. Introduction

Rapid increase in the calculation power and improvements of the analysis software allow the use of complex numerical analyses in tunnel design. One of the main objectives of such analyses is the optimum balance between accuracy and complexity, as the latter increases the time and cost of the design. While many tunnelling problems, especially in early design stage, can be analysed using simplified approaches including 2D finite element analyses, certain tunnelling problems such as EPB shield tunnelling in urban environment demand the use of advanced 3D numerical models to calculate, with reasonable accuracy, critical parameters such as tunnelling-induced ground surface deformations.

The main factors contributing in the complexity of the simulation of shield tunnelling are: (a) total and fluid muck pressure in the excavation chamber; (b) cutterhead overcut; (c) conical or telescopic-shaped shield; (d) void of the annular gap; (e) grout injection pressure at the tail void and its gradual consolidation; and (f) the structural system of the segmental lining (radial and longitudinal joints).

Several numerical approaches have been proposed for the simulation of shield tunnelling, adopting different assumptions and simplifications. Kasper and Meschke (2006) developed a 3D numerical model for shield tunnelling and investigated the influence of various parameters (face pressure, grout pressure etc.). In this model, grout and face pressures were simulated as prescribed pressures at the corresponding ground surfaces, with face pressure varying linearly with elevation, according to the bulk density of the muck. Nagel and Meschke (2011) investigated the influence of the steering gap on ground surface settlements. The interaction between the surrounding ground and the shield was simulated by a surface-to-surface contact algorithm, while a three phase model was employed for the consideration of fluid and gaseous flow within partially saturated soils.

Zhao et al. (2012) proposed two different approaches for modelling a gripper TBM and a single-shield TBM for deep tunnels in rock. The main difference between the two models is the method of the TBM advance and the inclusion of a suitable interface for shield-rock interaction in shield TBMs.

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Lambrughi et al. (2012) developed a 3D numerical model for EPB mechanised excavations. They modelled the steering gap between the shield and the surrounding ground using a thin layer of continuous linear elastic elements with very low stiffness, while grout pressure was modelled using continuum elements with an initial isotropic pressure equal to the injection pressure. A similar modelling technique for the steering gap was followed by Comodromos et al. (2014) for parametric analyses of the Thessaloniki Metro in Greece.

Segmental lining is usually modelled as a continuous cylindrical shell, neglecting longitudinal and ring joints. Several methods have been proposed to improve the resulting behaviour: Muir Wood (1975) and Lee and Ge (2001) proposed to discount the average rigidity of the lining using a factor depending on segment stiffness and the number of joints. However, both models were developed for plane strain conditions, thus neglecting the 3D effects resulting from the staggered configuration of the longitudinal joints, which tend to increase the overall stiffness of the structural system. Klappers et al. (2006) modelled each segment with a four-node plane shell element and compared the resulting internal forces with those of a standard 2D FE model with continuous shell lining. They concluded that the two models give very small differences. Arnau and Molins (2012) modelled the interaction between lining and surrounding ground using spring elements and examined the influence of the interaction between neighbouring rings in the structural response of the lining. Do et al. (2013) presented a 3D model of segmental lining where segments were simulated with linear elastic shell elements and joints between segments with rotational springs.

## 2. Description of the proposed numerical model

### 2.1. General characteristics

The proposed model is a 3D Finite Element model for shield-driven tunnelling based on the computer code Simulia Abaqus (Abaqus, 2011). It includes several components of EPB tunnelling, such as face thrusting with control of muck pressure on the excavation face, cutterhead overcut, conically-shaped shield with a shield-ground interface, tail gap, and an elaborate model for tail grouting (including time-dependent grout hardening) and segmental lining including longitudinal and ring joints.

The extent of the ground around the tunnel to be modelled by finite elements depends on tunnel geometry, ground conditions, the type of output (surface settlements, lining loads, wall convergence etc.) and the excavation method (Abel and Lee, 1973; Eberhardt, 2001; Graziani et al., 2007). Shield-driven tunnelling causes relatively small plastic-deformation zones around the excavation which permits to reduce the lateral extent of the FE model. Many researchers have published rules for the optimum boundary distance from the tunnel, in order to minimize boundary effects (Lambrughi et al., 2012; Zhao et al., 2012).

It is common practise in tunnelling to use symmetry with respect to a vertical plane including the tunnel axis and thus model only half of the domain. In the present case, this symmetry is not used, due to the presence of joints in the segmental lining. The modelled domain is an orthogonal prism consisting of 8-noded, hexahedral, full-integration, solid elements. Fig. 1 illustrates the general configuration of the numerical model; its size was determined by sensitivity analyses in order to balance calculation accuracy and computational cost. The tunnel diameter (D) is equal to 10 m, the overburden height (H) measured from the tunnel axis is set to 2D (20 m) and the total excavation length is 13D (130 m). The length of the excavation step is equal to the ring length (1.5 m). The ground is modelled as linear elastic - perfectly plastic, following the Mohr-Coulomb failure criterion.

### 2.2. Face and shield characteristics

Fig. 2 shows the details of the TBM-EPB model. The shield, cutterhead and bulkhead of the machine are modelled using 4-noded, quadrilateral, shell elements, while the excavation chamber and the EPB equipment are modelled with 8-node, hexahedral, solid elements; their main function is to simulate the weight and stiffness of the TBM which influences lifting of the tunnel invert, especially in shallow tunnels. The solid elements of the excavation chamber have distinct nodes from those at the excavation face. In addition to direct control of the face pressure, the unit weight of the elements in the excavation chamber can be adjusted to simulate the closed or open excavation mode of the machine. The TBM elements have a linear elastic behaviour, with the metal components assumed to be made of steel (Table 1).

Although real shields are either conical or telescopic (Maidl et al., 2012), many TBM models assume them to be cylindrical (Comodromos et al., 2014; Lambrughi et al., 2012). In the proposed model, the shield is modelled as conical with length 10.5 m, 4 cm tapering, 10 cm thick and includes a 2 cm cutterhead overcut (difference in the radius of the cutterhead and the front of the shield) and a 11–15 cm annular gap (difference in radius between the extrados at the rear of the shield and the extrados of the segmental lining) (see Fig. 2b and Table 1).

### 2.3. Modelling shield - ground interface

Shield conicity and the gap between the shield and the surrounding ground is modelled by a ca. 2 cm cutterhead overcut at the front end of the shield, increasing linearly to ca. 6 cm at the rear end of the shield. As the shield does not share nodes with the surrounding ground, the interaction between corresponding nodes of the shield and the ground is modelled by a suitable pressure-overclosure interface. A "softened" exponential pressure-overclosure relationship is employed (Fig. 3) because a "hard" one with infinite normal stiffness in compression and zero in tension (when the two surfaces are in contact), causes numerical instability. Thus, pressure transfer starts when the normal distance between the two surfaces falls below a prescribed small positive value $c_o$ and the contact pressure reaches a prescribed value $p_o$ then the two surfaces come in contact. The normal stiffness of the interface is equal to the slope of the curve defining the pressure-overclosure relationship and it is determined via the $c_o$ and $p_o$ parameters. The values of the two parameters are calibrated via parametric analyses within the stress range of the actual model, in order to ensure numerical stability and reasonable stress transfer. The interaction between the shield and the surrounding ground is assumed to be frictionless as the steering gap is usually lubricated. Validation results of the above interface are shown in a following section.

### 2.4. Modelling EPB face pressure

The EPB pressure on the excavation face is assumed to vary linearly with elevation according to a bulk density of the muck equal to 13 $kN/m^3$ (Kasper and Meschke, 2006; Sitarenios et al., 2015) and a reference pressure at the tunnel axis which is often equal to about 50% of the total horizontal geostatic stress ($\sigma_{ho}$).

### 2.5. Modelling tail grouting

In standard TBM operation, cement grout is injected at the rear end of the shield to fill the annular gap, i.e., the gap between the extrados of the segmental lining and the surrounding ground. In the proposed model, tail grouting is modelled by filling the annular gap with "grout elements" which are 8-node, hexahedral solid ele-