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3D Numerical Simulation of TBM Excavation for Predicting Surface Settlements - State of the Art

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ABSTRACT: Tunnels offer efficient transportation infrastructure in urban areas such as the Grand Paris Express in France. In urban areas, a densely built environment is exposed to the surface settlements caused by tunneling, and consequently, vulnerable buildings and infrastructure can be damaged. To mitigate this risk, the tunneling process is designed such that the surface settlements remain below a given threshold. Many numerical methods have been developed and are commonly used to simulate the surface settlements induced by a tunnel boring machine (TBM). The first objective of this paper is to present the state of the art of TBM excavation 3D finite element (FE) modeling. From this literature review, each modeling approach is compared concerning defining the geometry, meshing, setting the boundary conditions, and implementing TBM excavation parameters. Also, many simulations must be run to validate the modeling assumptions, calibrate the model using sensor data, and account for uncertainties in the boundary conditions, soil properties, and tunneling process. Thus, this literature review aims to identify the driving instruction parameters that impact settlements and methods to implement them in a 3D finite element model.

1 INTRODUCTION

The construction of underground tunnels in urban areas requires excavation works that induce surface settlements. Fagnoli et al. (2015) point out that vulnerable structures such as residential buildings, cultural heritage monuments, and underground services are exposed to surface settlements and may be damaged in a densely built environment. Engineers first estimate the settlement distribution using empirical and analytical methods. Then, soil-structure interaction studies are run to evaluate the built environment's vulnerability to tunneling-induced ground movements. Nevertheless, the empirically and analytically predicted settlement curves tend to be shallower and wider than those obtained with field observations, according to Cheng et al. (2007).

Although tunnel boring machine (TBM) technology has significantly reduced surface settlements in urban areas (Meschke et al. (2011)), significant ground movements can still be induced by several factors such as over-excavation, TBM shield conicity, the annular void behind the tail, mortar behavior, TBM guidance, ground losses at tunnel face, TBM stops for maintenance and working shifts, and excavation under challenging conditions as presented in Lambrughi et al. (2012). To ensure safety during shallower excavation work, sensors are installed to monitor real-time displacements induced by the TBM.

FE with 2D plane strain assumption is commonly used to simulate the surface settlements induced by a TBM and to investigate potential damage to surface buildings. TBM excavation has been studied through the tunnel axis's longitudinal but mainly transversal section. Different 2D numerical approaches based on the force control method (FCM) or the displacement control method (DCM) have been developed to represent each stage of a tunneling process:

1. Soil excavation,
2. Temporary support provided by the TBM shield to maintain the excavated soil wall,
3. Grout injection to fill the annular void between the TBM tail and the lining,
4. Lining installation and grout hardening.

Nevertheless, 2D Numerical models do not represent the 3D reality of the problem. Different studies that compare 2D and 3D models show that 3D models tend to bring more information such as the behavior of the excavation front, 3D surface settlements, longitudinal settlements through the tunnel axis, intermediate stress, and displacement states. Besides, spatial variability, non-linear soil properties, and complex interactions between the different materials involved in the excavation process (soil, TBM, lining, mortar, and adjacent structures) are reasons why many authors have used sophisticated constitutive models: Cheng et al. (2007), Kasper & Meschke (2006b), Kavvadas et al. (2017), Lambrughì et al. (2012), and Ochmanski et al. (2018).

To reliably estimate surface settlements during the tunnel construction, the 3D FE model must be calibrated and validated with monitoring data. Sensitivity analysis (Kasper & Meschke (2006a, 2004), Lambrughì et al. (2012), Melis et al. (2002), Namazi et al. (2012)) paired with back analysis (Zhao et al. (2015)) can be performed to calibrate the uncertain model parameters as the geological ones.

In this perspective, the first objective of this paper is to present the state of the art of tunneling process 3D numerical modeling in the specific context where (i) the tunneling process takes place in an urban area, (ii) the TBM digs in soft ground and (iii) the tunnel is in shallow ground. The second objective is identifying and implementing the TBM driving parameters that can be explicitly introduced and controlled in the 3D numerical simulations.

2 ARTICLES DATABASE CONSTITUTION

We selected a set of 78 articles (available at Papers Data Base) with the following research perspectives in mind: How to build a 3D numerical model of the TBM excavation process that:

1. Achieves balance between accuracy and calculation time
2. Integrates TBM driving parameters
3. Uses scripts to automate the model and make it parametric
4. Incorporates monitoring points and sections to run back analysis with field data.

These 78 papers were selected mainly by using online sources such as ScienceDirect, ResearchGate, HAL, ICE Virtual Library, SpringLink, ASCE Library, and Academia. "TBM", "EPB", "Settlements", "Prediction", "Parametric", "FEM", "Monitoring", "Mechanized Tunneling", "Numerical modeling", "Ground Movements", "Three-Dimensional" are keywords employed. 55 of the models presented in the selected papers are based on the finite element method (FEM), 21 on the finite difference method (FDM), 1 on the discrete element method, and 2 on other methods. For the 3D simulation of TBM excavation, the computer programs used are PLAXIS3D, CESAR-LCPC, FLAC3D, ABAQUS, MIDAS GTS, KRATOS, and others. Among these 78 papers, 40 were selected for in-depth analysis. The selection was made according to the number of quotes, the publication date, and the method used to simulate the excavation process. These 40 articles have an average quote per article of 63.9 compared to 59.96 in the 78 articles database. They were published between 2002 and 2022, and the FEM is mainly used to simulate the tunneling process (in 34 papers), while the FDM is used in the other papers. A total of 42 TBM excavation models are presented in these 40 papers.

3 MODELING TBM EXCAVATION WITH 3D FEM

3.1 *Geometry*

To build a 3D TBM excavation numerical model, model dimensions must be large enough to avoid boundary effects. In the papers analyzed, different recommendations are made to establish

the minimum size of the model (half-width, length, height) as a function of the depth H_t and diameter D_t of the tunnel:

- $(3H_t, 5H_t, 3H_t)$ in Ochmanski et al. (2018)
- $(2(H_t+4D_t), 2(H_t+4D_t), 3H_t)$ in Lambrughi et al. (2012) and Nematollahi & Dias (2019)
- $(11D_t, 21D_t, H_t + 3D_t)$ in Kavvas et al. (2017)

An average distance of $4D_t$ between the model basis and the tunnel axis has been established to avoid boundary effects at the bottom. 29 of the 42 models studied use symmetries concerning the vertical plane that contains the tunnel axis. This assumption is, however, generally not verified because there is no symmetry in the surface buildings and because of geological heterogeneity.

3.2 Step-by-Step procedure

First, the initial soil stress state is established. The vertical earth pressure is calculated by using the ground weight in saturated or unsaturated conditions. Then, lateral earth pressure is obtained by multiplying the vertical earth pressure by the earth pressure coefficient K_0 . Its value depends on the soil's behavior. When the soil stress state is assumed as isotropic, $K_0 = 1$. In an over-consolidated soil, a mechanism detected mainly in clay formations, $K_0 > 1$. K_0 can also be anisotropic in a horizontal plane as in Liu et al. (2008) to represent tectonic stresses. To estimate K_0 in granular soils, Nikakhtar et al. (2022) and Oh & Ziegler (2014) calculate K_0 as $K_0 = 1 - \sin(\phi)$ where ϕ is the internal friction angle. For cohesive soils, Losacco & Viggiani (2019) and Miliziano & Lillis (2019) use $K_0 = (1 - \sin(\phi)) * OCR^{\sin(\phi)}$ introducing the overconsolidation ratio OCR . At the end of this step, the displacement is reset to zero.

In the 42 numerical models we analyzed, a quasi-static approach is adopted where the TBM excavation process is simulated following a step-by-step procedure:

1. Soil excavation by deactivating a soil slice (generally the length of a lining ring). To initiate the process, the length of this slice is taken as equal to or greater than the length of the TBM shield by Fargnoli et al. (2015), Liu et al. (2008), Migliazza et al. (2009), Mirhabibi & Soroush (2013), Namazi et al. (2012), Rachdi (2019), Muhammed et al. (2019), Zhang et al. (2016)
2. Translation of the TBM shield with temporary support of the excavated surrounding soil
3. Grout injection to fill the annular void between the TBM tail and the lining
4. Lining installation
5. Grout hardening

In half of the models studied, the step-by-step procedure ends before the TBM reaches the longitudinal model limit. This impacts the calculation time and also avoids boundary effects. In 11 models, we noticed that the distance between the last slice of soil excavated and the longitudinal limit is approximately equal to $3D_t$ or H_t . Another way to avoid any boundary effects as the TBM enters or leaves the model is to consider monitoring points away from the longitudinal limits as in Kasper & Meschke (2006b), Melis et al. (2002), Meschke et al. (2011), and Miliziano & Lillis (2019). In Miliziano & Lillis (2019), it is recommended to place displacement monitoring points at a distance of $7D_t$ from the TBM entry longitudinal section and $13D_t$ to the opposite section.

3.3 TBM parameters in the model

Integrating the TBM driving parameters into the model is essential to properly simulate the TBM excavation process.

3.3.1 TBM, mortar, and lining models

The main components involved in a TBM excavation process are the soil layers, TBM structure, lining, and grout. Different options to model those pieces have been adopted: deformable materials, rigid bodies (undeformable elements), and "fictive" representation. For deformable materials, except for soil layers where more complex behavior is considered, the mechanical behavior is mostly explained by an isotropic homogeneous elastic law.

3.3.2 Face pressure

During tunneling, the TBM shield maintains the excavation face under pressure to prevent the soil from collapsing on the cutterhead. In soft ground, this phenomenon can significantly impact

surface settlements (Kasper & Meschke (2006a), Lambrugh et al. (2012)). Different TBM technologies have been developed to pressurize the soil. Slurry TBM injects a mixture of soil materials and slurry into the excavated chamber to stabilize the front. Earth pressure balance (EPB) TBM keep the excavated soil in the excavated chamber to pressurize the front. In most papers, the front pressure is simulated by a horizontal load at the interface between the TBM and the excavated soil. Even if the effective state stress is considered in the soil, the pressure applied on the excavated face corresponds to the total stress (Losacco & Viggiani (2019), Meschke et al. (2011), Ochmanski et al. (2018, 2020)). To represent vertical variation, hydrostatic distribution is considered for the face pressure: $p_f(z) = \sigma_h(z_0) + K_0\gamma(z - z_0)$ with $\sigma_h(z_0)$ the horizontal total stress at the tunnel key level, γ the excavated soil weight, and K_0 the coefficient of earth pressure. TBM data recording during tunneling operation sometimes show that the face pressure does not increase systematically linearly with depth (Lambrugh et al. (2012)). A uniform distribution can be justified in some specific cases: Founta et al. (2013), Lambrugh et al. (2012), Migliazza et al. (2009), Mirhabibi & Soroush (2013), and Nikakhtar et al. (2022). Jenck & Dias (2004) do not simulate the front pressure but block the horizontal displacements of the excavation face in the FE model.

3.3.3 Conicity and overcut

The TBM shield shape is conical to reduce the friction between the TBM shield and the surrounding soil. Kasper & Meschke (2006b) and Lambrugh et al. (2012) show that the voids induced by the conical shape and the consideration of overcutting impact the surrounding soil displacements. The shield conicity has been explicitly modeled by Broere & Brinkgreve (2002), Kasper & Meschke (2006a, 2006b, 2004), Kavvadas et al. (2017), Losacco & Viggiani (2019), Melis et al. (2002), and Miliziano & Lillis (2019). When the TBM is not physically modeled, the conicity can be implemented by a "fictitious" law on displacements (Dias & Kastner (2013), Zhang et al. (2016)) or forces (Michalski et al. (2011)), or simulated by a volumetric material filling the space between the surrounding soil and the TBM (Lambrugh et al. (2012)).

3.3.4 TBM jack forces

Thrust jacks ensure the advance and guidance of the TBM shield. To study their impact on the surrounding soil, Barla et al. (2011), Dias & Kastner (2013), Founta et al. (2013), Nematollahi & Dias (2019), and Ochmanski et al. (2018, 2020) have modeled jacks as horizontal forces or loads in the direction opposite to that of the TBM. These forces are applied on nodes at the circumferential interface separating the tail and the last lining ring.

3.3.5 Grout injection

Pressurized grout fills the annular void between the TBM tail and the lining as well as it supports the wall of excavated soil and reduces surface settlements. One approach to model it consists in applying a surface load along the tunnel circumference. This stress is activated a few meters after the TBM tail and before the beginning of the grout consolidation phenomenon (Broere & Brinkgreve (2002), Fargnoli et al. (2015), Litsas et al. (2015), Liu et al. (2017), Losacco & Viggiani (2019), Mirhabibi & Soroush (2013), Nematollahi & Dias (2019), Nikakhtar et al. (2022), Ochmanski et al. (2018), Rachdi (2019), Zhang et al. (2016)). Another method consists in activating a volume material between the excavated soil and the lining with an internal pore pressure to simulate the injected pressure (Afifipour et al. (2011), Kasper & Meschke (2006a, 2006b, 2004), Kavvadas et al. (2017)). To consider the grout weight and to balance the increase of the stresses of the surrounding soil with the depth, a linear variation of the grouting pressure is introduced in 14 of the 42 models studied. Instead of hydrostatic distribution, a uniform distribution has been adopted by Afifipour et al. (2011), Fargnoli et al. (2015), Founta et al. (2013), Kavvadas et al. (2017), Lambrugh et al. (2012), Litsas et al. (2015, 2017), Losacco & Viggiani (2019), Mirhabibi & Soroush (2013), Mohammadzadeh et al. (2021), Nikakhtar et al. (2022).

3.3.6 Grout consolidation

Two mechanical behaviors of the grout can be considered in a model of TBM excavation. The first one is a liquid phase under pressure. The second one is a solid material without internal pore pressure characteristics. The further the TBM is away from the grout, the more consolidated the grout is. In most models we analyzed, this consolidation phenomenon is simulated as a time-dependent process. The hardening process in 15 of these models is spread over several

stages. The grout Young modulus increases and the Poisson ratio decreases while it consolidates. The number of hardening steps involved in this process depends on certain model parameters. TBM stops for maintenance, working swap, or lining installation, and the TBM velocity significantly impacts the consolidation duration (Kasper & Meschke (2006b), Lambrughi et al. (2012), and Meschke et al. (2011)). To implement the TBM velocity V_A , the grout hardening duration $t_{hardening}$, and the TBM stop duration t_{stop} in the quasi-static model, a formula to calculate the number of steps $N_{hardening}$ involved in the hardening process has been established:
$$N_{hardening} = \frac{V_A(t_{hardening} - t_{stop})}{l_{step}}$$
 with l_{step} the length of a slice of excavated soil. This process can also be simulated in two stages as in Dias & Kastner (2013), Lambrughi et al. (2012), Melis et al. (2002), Nematollahi & Dias (2019). First, the liquid grout is activated. Then, the mechanical properties of liquid grout change immediately for those of solid mortar.

3.3.7 TBM weight

Even if the TBM weight seems to have a small impact on the surface settlements compared to other parameters, according to Kasper & Meschke (2006a), different ways to consider it in the numerical model have been studied. In cases where the TBM shield is modeled by surface or volume components, a suitable density of TBM elements was considered by many authors. The weight of the shield, the excavated chamber, and the equipment must be considered. Otherwise, a vertical load is applied along the wall of the excavated soil. To simulate the influence of the TBM backup train, an appropriate vertical load is applied to the lining (Broere & Brinkgreve (2002), Kasper & Meschke (2006a, 2006b, 2004), Melis et al. (2002), and Meschke et al. (2011)).

3.3.8 Lining joints

A few previous studies, Dias & Kastner (2013), Losacco & Viggiani (2019), and Ochmanski et al. (2018), have revealed that the consideration of joints in the mechanical behavior of the concrete lining does not significantly affect the ground displacements predicted by FEM simulation. Nevertheless, to evaluate the strain and the intern stresses in the lining, the joint patterns between longitudinal rings and between ring segments have to be taken into account. The major effect of joints is a reduction of the concrete lining stiffness (Ochmanski et al. (2018, 2020), Rachdi (2019)). More complex joint models were developed by Dias & Kastner (2013), Kavvadas et al. (2017), Litsas et al. (2015) to evaluate the response of the actual lining mechanical structure to the tunneling process.

3.3.9 Interactions between elements

In FE models, contacts are considered through interface relationships. To simulate the normal contact between two different parts, exponential "softened" pressure-overclosure (Kavvadas et al. (2017), Litsas et al. (2015, 2017), Losacco & Viggiani (2019)), hard contact (Litsas et al. (2015), Melis et al. (2002), Ochmanski et al. (2018, 2020)), and the relationship established by Laursen have been observed in many papers (Meschke et al. (2011)). Exponential "softened" pressure-overclosure and hard contact are mechanical rules introduced in the ABAQUS FEM software. The "soft" exponential contact law needs to be calibrated, but it does not show any errors (Litsas et al. (2015)). On the contrary, the "hard contact law" does not require calibration but it is often the source of computational errors during FE simulation. Otherwise, the friction phenomenon is considered as a tangential contact relationship between two independent objects. In the 40 papers analyzed, the Mohr-Coulomb in Barla et al. (2011), Kasper & Meschke (2006a, 2006b, 2004), and Herzog in Ochmanski et al. (2018, 2020), behavior are the most common friction models. In some papers, Litsas et al. (2015) and Losacco & Viggiani (2019), the interface between the TBM shield and the surrounding soil is considered lubricated, and the contact is therefore assumed to be frictionless.

3.4 Soil model

3.4.1 Mechanical behavior

The prediction of the surface settlements induced by the tunneling process depends significantly on the mechanical behavior of the soil. The more complex the soil model, the closer the prediction of the shape and maximum value of surface displacements is to the field data (Cheng et al. (2007), Jenck & Dias (2004), Lambrughi et al. (2012)). Nevertheless, complex soil behavior induces high computational time (Melis et al. (2002), Migliazza et al. (2009)), and high laboratory costs (Zhao

et al. (2015)), due to a large number of parameters to be determined. **Table 1** compares soil models found in the literature.

Table 1. State of knowledge on the mechanical behavior of soils used in FEM simulation of tunneling

Soil Model	Behavior	Complexity	Soil type	NboPar*	NbPap**
Mohr-Coulomb (MC ⁽¹⁾)	Linear	+	-	4	19
Drucker-Prager (DP ⁽¹⁾)	Linear	+	-	5	2
Cap Yield Soil (CPSoil)	Non-linear	++	-	10	2
Hypoplastic $a^{(2)}$	Non-linear	++	Granular	8	5
Hypoplastic $b^{(3)}$	Non-linear	++	Cohesive	5	3
Hypoplastic $a^{(2)}$ + ISC ⁽⁴⁾	Non-linear	+++	Granular	13	5
Hypoplastic $b^{(3)}$ + ISC ⁽⁴⁾	Non-linear	+++	Cohesive	11	3
Modified Cam Clay	Non-linear	++	Cohesive	8	4
Hardening Soil Model (HSM)	Non-linear	++	-	9	5
HSM Small Strain	Non-linear	+++	-	13	2

*Number of parameters needed without mentioning the density, K_0 and the permeability, **Number of papers over forty studied where the soil behavior is mentioned, ⁽¹⁾ yield criterion of plasticity, ⁽²⁾ Von Wolffersdorf 1996, ⁽³⁾ Masin 2005, ⁽⁴⁾ Intergranular Strain Concept

3.4.2 Water conditions

For the sake of simplicity, because of imprecision or the absence of groundwater, the assumption of excavating in dry conditions has been adopted in some models (Dias & Kastner (2013), El Jirari (2021), Gaudry & Givet (2017), Lambrughi et al. (2012), Michalski et al. (2011), Saleh et al. (2022), and Soomro et al. (2018)). Otherwise, the choice between drained or undrained conditions is decided after balancing several factors, such as soil permeability and TBM velocity in Lambrughi et al. (2012). For instance, for high soil permeability and low TBM velocity, pore pressure dissipates rapidly, and fully drained conditions are assumed as in Fagnoli et al. (2015), and Jenck & Dias (2004). The assumption made above can be discussed in the case of low soil permeability and low TBM speed. To avoid errors due to simplifications, pore pressure is modeled, and undrained conditions are presumed. The pore pressure increases linearly with depth and is zero at the water table. To account for groundwater flow, the pore pressure modeled has to be coupled with permeability (Litsas et al. (2015), Ochmanski et al. (2018), Oh & Ziegler (2014), and Zhang et al. (2016)).

3.4.3 Meshing

Many different FE meshes model the soil skeleton and pore pressure. Each mesh element presented in **Table 2** is optimized and adapted for certain mechanical behaviors. Only the soil mesh has been considered in **Table 2**. Besides, it was noted that linear bricks or tetrahedral elements were mainly used to mesh the lining, the grout, and the shield of the TBM.

Table 2. State of knowledge on 3D finite elements used in FEM simulation of tunneling

Shape	Interpolation	Nb of nodes	Nb of integration points	Pore pressure	NbPap*
Brick	Linear	8	2x2x2 (fully)	Yes	2
Brick	Linear	8	1 (reduced)	No	1
Brick	Linear	8	2x2x2 (fully)	No	7
Brick	Quadratic	20	3x3x3 (fully)	Yes	1
Brick	Quadratic	20	2x2x2 (reduced)	No	1
Brick	Quadratic	20	3x3x3 (fully)	No	4
Tetrahedron	Quadratic	10	4 (fully)	Yes	1
Tetrahedron	Quadratic	10	4 (fully)	No	6
Wedge	Quadratic	15	9 (fully)	No	2

*Number of papers over forty studied where the mesh element is mentioned

3.5 Buildings, piles

In 40% of the models we studied, the interaction between buildings, piles or foundations, and the soil surface is simulated. It has been noticed that the interaction between soil and structure has a non-negligible impact on the shape and the amplitude of the settlements induced by tunneling.

4 CONCLUSION

The literature review in this paper reveals the key parameters that must be considered to predict surface settlements induced by the TBM excavation process (**Table 3**). It also reveals that some tunneling driving parameters can be explicitly considered in 3D FE simulation. Future work includes (i) developing and calibrating a 3D FE model of the TBM excavation process (ii) implementing statistical approaches (Ninic et al. (2022)), to compute an optimal set of TBM driving instructions to keep induced settlements under a given threshold.

Table 3. Assumptions used for the simulation of the TBM excavation process

Model Parameters	Implementation within the model	Type
TBM/Grout/Lining	Volumic material	Multiple parts
Face Pressure	Apply a depth-dependent pressure at the interface between the ground and the face of the TBM	Boundary condition
Conicity	Conical shape of the TBM shield part	Geometry/Interaction
Overcutting	Excavated soil diameter superior to TBM face diameter	Geometry/Interaction
TBM jack forces	Apply horizontal forces on nodes located at the interface between the tail and the lining	Boundary condition
TBM weight	Assign a density to the TBM elements	Material properties
Injected Pressure	Apply a hydrostatic pressure to the soil wall just after the TBM tail	Boundary condition
Hardening of the grout	Deactivation of the injected pressure and time-dependent behavior (from liquid to solid state)	Material properties
Lining joints	Reduction of the stiffness of the concrete lining	Material properties

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