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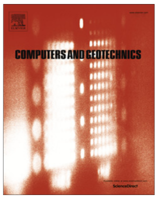

Research Paper

Computational modelling of the mechanised excavation of deep tunnels in weak rock

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ABSTRACT

Tunnel Boring Machine (TBM) tunnelling in weak rock associated with high overburden is very demanding due to the difficulties in predicting the complex interactions between the rock mass, the tunnel machine, its system components, and the tunnel support during excavation/construction. These factors affect the performance and even the feasibility of a TBM drive (sticking of the cutterhead and jamming of the shield may occur). In this respect, several computational models such as the Convergence–Confinement Method (CCM), axially symmetric model and three-dimensional (3D) simulation have been developed in the literature. Among these models, this paper presents three modelling techniques (i.e., a 3D simulator using the Finite Element Method (FEM), an axisymmetric model using the Finite Difference Method (FDM) and an LDP (Longitudinal Displacement Profile) approach based on the CCM), and applies them to the Headrace Tunnel from the Kishanganga Hydroelectric Project in India. The three approaches are not considered to be alternatives but rather complementary to each other, depending on the real situation. The LDP approach is a simplified analytical method but is still efficient to provide a conceptual framework for evaluating the ground-shield interplay during mechanised excavation. The FDM axisymmetric model represents a powerful tool (i.e., with a large deformation scheme available) for the simulation of ground behaviour and its interaction with the machine components, especially in the case of weak rocks with high deformability. However, when the conditions violate the important assumptions underlying these two approaches, true 3D numerical analyses are necessary, which consider all the TBM components. Finally, the paper highlights the potentials of the 3D simulator to model the basic features (i.e., stepwise conicity of the shield, backfilling layer and anisotropic in-situ stress state) of a shield-driven deep tunnel, which determine the tunnel's behaviour and its response to TBM advancement. The obtained results show that the 3D nature of the complex interactions and the in-situ state of stress, including the nonlinear behaviour can be better reproduced in a 3D simulation than in the other two methods.

1. Introduction

Large convergences are often encountered in tunnel excavation that combines high overburden with poor ground properties. In particular, rapidly developing convergences have been observed and documented in a number of shield-driven tunnels in the past [30]. Mechanised excavation with Tunnel Boring Machines (TBMs) under such conditions is getting the most attention, given the technological developments that have recently been made. For an extended review of the literature with respect to the experiences and countermeasures (such as over-excavation technology, shield layout, thrust systems, and pre-ground treatment) available to address difficult ground conditions, the reader can refer to Ramoni and Anagnostou [30].

Methods are needed in the designing stage to effectively address the complex interactions between the rock mass, the tunnel machine, its system components, and the tunnel supports. The three-dimensional problem in nature, however, still poses a challenge to making a reliable computational model associated with the nonlinear behaviours. The weak rock model (physical nonlinearity), large deformation (geometrical nonlinearity), and discontinuous behaviour at the boundary conditions (boundary nonlinearity) between the rock mass and the structural elements

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Nomenclature

List of symbols

A	surface area
c	cohesion (Mohr–Coulomb)
D	excavation diameter
E	Young's modulus
E_s	Young's modulus of the shield
E_{eq}	radial stiffness of the shield
F_f	thrust force to overcome friction
G	shear modulus
K	bulk modulus
k	lateral pressure coefficient
K_l	stiffness of the lining
L	shield length
L_0	length of the shield in contact with the ground
N	number of elements in the shield surface
p	ground pressure
$\bar{p}$	cutterhead pressure
p_{fict}	fictitious internal pressure
p_s	ground pressure on the shield or lining
r	shield radius
R	excavation (tunnel) radius
R^*	normalised plastic radius
R_{pl}	radius of plastic zone
s	shield thickness
S	contact surface of the shield in contact with the ground
u	final radial displacement
u^*	normalised convergence
u_f	displacement at the face, so-called "pre-deformation"
u_{max}	maximum radial displacement
u	radial displacement
UCS	uniaxial compressive strength
X^*	normalised position to the face
Δg	gap between the shields and the rock mass
Δr	conicity
ΔR	over-excavation in radius
Δz_{min}	smallest width of an adjoining zone in the normal direction
ε	strain
ε_{pi}	principal plastic strain
ε_{pl}	equivalent plastic strain
ν	Poisson's ratio
σ	stress
σ_n	normal stress
σ_0	initial stress
σ_h	horizontal stress
σ_v	vertical stress
β	surface reduction coefficient
τ	shear stress
φ	friction angle (Mohr–Coulomb)
ψ	dilation angle (Mohr–Coulomb)

(shields and segmental lining) represent important numerical difficulties and significantly limit the computability [6].

TBM tunnelling in poor ground conditions is, therefore, very demanding due to the difficulties in predicting tunnel behaviour at the design stage and the problems during construction that affect the performance and even the feasibility of a TBM drive (sticking of the cutterhead and jamming of the shield may occur). In this respect, several analytical solutions and numerical models (axisymmetric and 3D models) have been proposed in the literature. The Convergence–Confinement Method (CCM) represents the simplest model but its important assumptions dramatically limit its applicability [34]. Axisymmetric models can provide an in-depth investigation of the interaction processes during mechanised excavation, but the most advanced design and analysis method consists of 3D modelling, which considers all the TBM components.

After a brief description of these models, this paper presents three available approaches, namely, a 3D simulator (using the Finite Element Method (FEM)), which was recently developed by Zhao et al. [40], an axisymmetric model (using the Finite Difference Method (FDM)) and a LDP (Longitudinal Displacement Profile) approach (based on the CCM). An example from the Headrace Tunnel from the Kishanganga Hydroelectric Project in India is also illustrated, with attention paid to the comparison of the three models to check their pertinence and precision of the representation of the ground-TBM interactions. Furthermore, the paper also carries out systematic investigations on the sensitive factors that dramatically change the tunnel's behaviour, including the conicity (stepwise reduction of the shield diameter), backfilling grout layer and anisotropic in-situ stress state, to highlight the potentials of the 3D simulator.

The proposed modelling techniques concern only the short-term behaviour of the ground and its response to TBM tunnelling near the face (i.e., the machine area). Note, however, that the structure loading (i.e., the shield and the lining) may also be influenced by time-effects. This is particularly pronounced when weak rocks are encountered in combination with a high overburden and high water pressure. This aspect is not dealt with in the present paper. For computational investigations into the effects of creep or pore pressure dissipation the reader is referred to Debernardi and Barla [10] and Hasanpour et al. [16], and Ramoni and Anagnostou [29], respectively.

2. Design and analysis methods

2.1. Numerical models

The processes of stress transfer resulting from rock mass-structural support interactions in the vicinity of the tunnel face is neither plane stress nor plane strain. To numerically model TBM excavation in rock masses, only the axisymmetric and fully 3D models can take into account the excavation process and the sequence of lining installation, thus avoiding the errors introduced by the assumption of plane strain conditions [8]. Recent reviews on these models, especially on the 3D models available, can be found in Zhao et al. [40].

The most relevant axisymmetric simulation has been proposed by Ramoni and Anagnostou [30,32], who have studied the case of squeezing ground using a steady-state method. The numerical model has been formulated in a frame of reference that is fixed to the advancing heading, similar to a furrow moving along a ship [25]. The one-step solution method corresponds to the limiting case of a step-by-step model with zero round length [8]; for this reason, this method is well suited to reproduce a continuous TBM excavation process. Based on extensive parametric studies, Ramoni and Anagnostou [31] developed dimensionless design nomograms that allow a quick preliminary assessment of the thrust force required to overcome the shield skin friction.

2.2. Convergence–confinement method

The CCM is a 2D simplified approach considering 3D ground-support interactions near the tunnel face (due to the spatial effect