Engineering Structures 47 (2013) 35–44

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Parallelized computational modeling of pile–soil interactions in mechanized tunneling

Günther Meschke *, Jelena Ninić, Janosch Stascheit, Abdullah Alsahly

Institute for Structural Mechanics, Ruhr University Bochum, Universitätsstr. 150, 44780 Bochum, Germany

ARTICLE INFO

Article history:
Available online 7 September 2012

Keywords:
Finite element method
Mechanized tunneling
Pile foundation
Domain decomposition
Frictional contact
Anchors

ABSTRACT

The construction of tunnels in soft ground causes short and long term ground deformations resulting from the disturbance of the virgin stress state of the soil and the changing pore water conditions. In particular in urban tunneling, in each stage of the construction process, interactions between the construction process, the soil and existing building infrastructure need to be evaluated to limit the risk of damage on existing buildings and to decide on appropriate mitigation measures. Besides conventional tunneling, mechanized tunneling is a well established and flexible technology in particular in urban areas, which allows for tunnel advances in a wide range of soils and difficult conditions. The paper presents a finite element model for the simulation of interactions between mechanized tunnel construction, the surrounding soil and existing buildings resting on pile foundations in the framework of a process-oriented simulation model for mechanized tunneling. The performance of the model is demonstrated by means of selected prototype analyses. As a consequence of the high computational demand connected with this type of spatio-temporal simulations, problem specific parallelization techniques are investigated to increase the numerical efficiency of the numerical analyses.

1. Introduction

Tunneling in urban environment has become an essential part of infrastructural development worldwide. In this context, the protection of vulnerable buildings from damaging effects of the tunnel construction is a challenge, in particular in soft ground conditions and tunneling with low overburdens. Besides conventional tunneling, mechanized tunneling is a well established and flexible technology in particular in urban areas, which allows for tunnel advances with small cover depths and in different geotechnical conditions including water saturated soft soils. In soft, partially or fully saturated ground conditions, the tunnel construction process causes short and long term ground deformations resulting from the disturbance of the virgin stress state of the soil and the changing pore water conditions. During the construction process in urban tunneling, interactions between the construction process and the environment need to be evaluated to limit the risk of damage on existing buildings and to decide on appropriate mitigation measures. To this end, realistic numerical models able to appropriately consider the interactions between the mechanized tunneling process, the soil and existing surface structures and their foundations during the complete construction process are required. For an adequate representation of the interactions of the tunneling process with the built environment, a number of submodels have to be combined: a realistic model of the tunneling process including the various support methods, a ground model that captures the main characteristics of the ground behavior under tunneling-induced disturbance, and a model for the aboveground structures and their foundations taking into account frictional contact with the ground. In mechanized tunneling, the tunneling process involves various components (the tunnel boring machine (TBM), the soil and groundwater conditions, lining, steering via the hydraulic jacks, tail void grouting and various types of face support) and their relatively complex mutual (time-dependent) interactions. In conventional tunneling by means of the New Austrian Tunneling Method (NATM), besides the staged excavation process, the interactions between the supporting shotcrete shell and grouted anchors and the ground need to be considered.

Although the continuous increase of computing power and the considerable progress in computational modeling have stimulated the development of numerical simulation models in tunneling since the early 1980s, compared to the large number of models developed in the context of NATM tunneling (see, e.g. [1] and references therein), only a limited number of fully three-dimensional numerical models exist for shield tunneling due to its considerably more complex nature, see, e.g. [2–5]. A prototype for a process-oriented three-dimensional finite element model for simulations of shield-driven tunnels in soft, water-saturated soil has been proposed in [6] and successfully used for systematic numerical studies of interactions in mechanized tunneling [7]. This model has been recently extended for the process-oriented simulation

---

* Corresponding author.
E-mail address: guenther.meschke@rub.de (G. Meschke).

0141-0296/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2012.07.001

of shield-driven tunnels in partially saturated soft soils (see, e.g. [8], using a more advanced, flexible software architecture, an automatic model generator [9], a more suitable elasto-plastic model for soft ground conditions [10] and a three-phase model for soft soils to represent face support by means of compressed air in addition to general partially saturated conditions [11]. This model is augmented by components to account for piles embedded in the ground at arbitrary positions and orientations to consider interactions between the tunneling process and existing structures on pile foundations. Here, the interactions between the pile foundation and the surrounding soil is characterized by the coupling of deformations along the interface and at the tip of the pile, and by possible relative slip deformations between the piles and the soil.

Several finite element models have been proposed for the representation of soil–pile interactions. In an early approach by Desai and Appel [12] volume elements for both soil and piles, connected by a thin layer of interface elements have been used. This method, however, requires compatibility of both finite element meshes and hence a rather fine discretization of the soil in the vicinity of the pile. More recent formulations apply surface-to-surface contact conditions [13–15] or define a void in the soil mesh of the dimensions of the pile that is attached to beam elements by means of node-to-surface contact conditions to account for the soil–pile interactions [16]. Although these approaches do not require compatible discretizations for the piles and the soil, these formulations still require a priori consideration of the location and orientation of the piles in the geometrical setup of the model. An embedded pile formulation proposed by Sadek and Shahrour [17] accounts for piles as beam elements that are discretized independently from the soil. Their interaction with the soil is modeled by detecting intersections of soil and pile elements and inserting interface nodes. Since only one pile may intersect with a finite soil element, the discretization effort is considerable in case of pile groups.

In the paper, a recently developed embedded pile formulation is presented in the context of modeling interactions between the tunneling process and existing buildings resting on pile groups. The pile element allows to consider frictional contact between piles and the soil surface and pile tip resistance along arbitrarily oriented piles embedded within soil elements. As an advantage compared to existing models, the current formulation does not require the geometry nor the discretization of the soil to be compatible with the layout of the piles. All interaction conditions are enforced in control points of the embedded beam elements forming the piles. The developed embedded pile formulation can also be used to represent rock reinforcement by means of anchors or pipe roofs within the ground surrounding the excavation domain in conventional tunneling [18]. This feature is also addressed in this paper.

To reduce the large computation times connected with the complex process-dependent simulation model, parallelization techniques on shared and distributed memory systems have been developed [19], adopting parallelization strategies to the non-standard finite element technology applied in the simulation model.

The remainder of the paper is organized as follows: Section 2 contains a summary of the main features of the numerical simulation model for shield tunneling employed for the presented analyses. The extension of this model using a frictional embedded pile formulation is described in Section 3. Two numerical examples are presented to demonstrate the capabilities to model the interaction between machine driven tunnel construction underneath a high-rise reinforced concrete building and the use of the embedded pile formulation for modeling rock reinforcement in conventional tunneling. Finally, Section 4 addresses parallelization techniques employed to speed up the computation times for the computationally highly demanding simulation model.

2. Computational simulation model for mechanized tunneling

The main components of a finite element model for shield driven tunneling have been presented in [20,21,11]. Therefore, the model is only briefly described here. It has been implemented in the object-oriented finite element framework KRATOS [22] and is denoted as `ekate` (Enhanced Kratos for Advanced Tunneling Engineering). Its main design goal is to provide an efficient yet realistic simulation environment for all interaction processes occurring during machine driven tunnel construction. It includes all relevant components of the mechanized tunneling process as sub-models, representing the partially or fully saturated ground, the tunnel boring machine (TBM), the tunnel lining, hydraulic thrust jacks and the tail void grouting, which are interacting with each other by means of algorithmic coupling. The ground model is formulated within the framework of the theory of porous media and accounts for the coupling between the deformations of the solid phase and two fluid pressures (incompressible liquid and compressible air phases) taken as primary variables. Fluid flow through the pores is described using Darcy's law in combination with the concept of relative permeabilities, using the soil–water characteristic curve (SWCC) according to VAN GENUCHTEN. The material behavior of the soil skeleton is modeled by means of a nonlinear elasto-plastic constitutive law for clays and sands, proposed in [10]. Quadratic (linear) approximations are used for the approximations of the displacements (pore fluid and air pressures). A detailed description of the multi-phase model for partially saturated soils and its spatial and temporal discretization is given in [23].

Fig. 1 shows the main components involved in mechanized tunneling (left) and their representation in the finite element model (right). The TBM is modeled as an independent, deformable body connected along the shield skin to the soil by means of frictional contact conditions; the weight of the structural and machinery parts of the machine are accounted for. The segmented tunnel lining is represented by volume elements that are step-wise activated during the process simulation. The segmentation of the lining is accounted for by means of a homogenized stiffness reduction according to [24]. The lining tube is furthermore used as counter-bearing for the hydraulic jacks thrusting forward the shield machine. The hydraulic jacks, represented by truss elements take the front surface of the least activated lining segment as the counter-baring for the hydraulic jacks thrusting forward the shield machine by means of prescribed strains induced in the elements. The elongation of each jack element is controlled by a steering algorithm that allows for counter-steering against weight-induced dropping of the TBM to keep the path of the machine on the prescribed tunnel alignment. The simulation of the advancing process for arbitrary alignments requires a continuous adaption of the finite element mesh in the vicinity of the tunnel face in conjunction with the steering algorithm for the TBM advance and appropriate algorithms for the transfer of internal variables. A new technique to automatize the process of mesh generation utilizing a hybrid mesh approach in which a new computational mesh in the vicinity of the tunnel face is automatically generated within the advancing process, is introduced (Fig. 2a). To model the pressurized grouting mortar used to fill the gap between lining and ground, a two-phase (hygro-mechanical) formulation similar to the one used for the ground model is applied. Here, the grouting pressure is applied as pore water pressure to the fresh mortar. Stiffening of the grouting mortar is considered while the pore water pressure may dissipate according to an infiltration process into the surrounding ground. The heading face support can be adapted to the requirements posed by the specific TBM. Depending on the type of face support in hydro- and earth-pressure balance shields the pore water pressure, and the total or effective stresses mechanical pres-