Numerical simulation of soil–support interaction as basis for the day-to-day decision process in NATM tunnel excavations

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Abstract

In this paper, the soil–support interaction for tunneling processes according to the New Austrian Tunneling Method (NATM) is investigated by means of plane-strain numerical simulations. The studies performed encompass different types of soil (cohesive and granular) and two types of support means (shotcrete lining and jet-grouted soil). As regards the latter, the early-age behavior of the cement-based components is taken into account by means of a coupled chemomechanical approach. The obtained results provide insight into the benefits gained from the employed support means during NATM tunneling in different geological conditions, serving as the basis in the day-to-day decision process at NATM construction sites.

Keywords: Tunneling; NATM; Soil; Shotcrete; Jet grouting; Chemomechanics; Soil–structure interaction

1. Introduction

The New Austrian Tunneling Method (NATM), which is frequently used for the construction of underground infrastructure, is characterized by a strong interaction between the deforming ground and the continuously adopted support means. The latter are installed to provide the safety for the working crew and to minimize settlements in case of tunneling with low overburden, avoiding damage of surface buildings and infrastructure.

The proper layout of the support during NATM tunnel excavation is obtained from day-to-day decisions, which are based on a closed control cycle consisting of 'monitoring – interpretation of results – adaptation of support means'. Whereas displacement measurements (tunnel convergence and settlements) provide insight into the actual safety at the construction site, numerical schemes are required in order to assess the impact of the adaptation of support means for the next excavation steps. In this paper, the contribution of numerical tools to the mentioned day-to-day decision process in NATM tunneling is illustrated for two support means, namely shotcrete lining and jet-grouted soil, installed in different geological conditions.

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2. Material models

Numerical simulations of the NATM tunneling process need to capture the interaction between the hardening support means (hydrating shotcrete lining and jet-grouted soil) and the viscous soil. Thus, the employed material models must account for the time-dependent behavior of both soil and support, as will be outlined in the following subsections.

2.1. Material models for soil

In order to cover tunneling situations in different geological conditions, two material models for soil were considered in this study. These models are employed to describe the mechanical behavior of either cohesive or granular soil:

- For the simulation of the behavior of granular soil, the Mohr–Coulomb failure criterion is chosen. This criterion is well suited to describe the failure characteristics of granular materials under moderate compressive loading states. Accounting for the experimentally observed moderate volume dilation during shear deformations [1], a non-associative flow rule is adopted. Frictional hardening is considered in order to consider the increase of the mobilized friction under shear loading.
- The behavior of cohesive soil is described by the

Table 1
Material parameters for sand and clay

	Sand	Clay
Unit weight of material, γ (MN/m^3)	0.017	0.0235
Young's modulus, E (MPa)	45	–
Poisson's ratio, v	0.35	–
Initial friction angle, φ_i (°)	20	–
Peak friction angle, φ_p (°)	30	–
Cohesion, c (MPa)	0.001	–
Peak dilation angle, ψ_p (°)	4	–
Internal variable α_{MC} at $\varphi = \varphi_p$	0.03	–
Fluidity parameter, τ (h)	0.15	–
Slope of the normal compression line, λ	–	0.161
Slope of the unloading–reloading line, k	–	0.062
Slope of the critical state line, M	–	0.88
Initial specific volume, v_o	–	2
Initial size of the elastic domain, q_o (MPa)	–	0.80
Tensile strength, T (MPa)	–	0.23
Amount of coupling in elasticity, $\bar{\alpha}$	–	15
Viscosity of the soil, η (MPa h)	–	3

Cam–Clay model, emanating from the critical state theory. Following experimental observations, a non-linear elastic material response, characterized by the compression and shear moduli depending on the hydrostatic pressure, is employed. Associative plasticity is adopted to describe the evolution of plastic deformations. The size of the ellipsoidal yield surface is controlled by a volumetric hardening/softening law.

In order to incorporate the creep behavior of soils, both material models were extended towards viscoplasticity. Hereby, the Duvaut–Lions and the Perzyna models are employed for the Mohr–Coulomb and Cam–Clay criterion, respectively (for details, see [2]). The material properties employed in the numerical simulations are listed in Table 1.

2.2. Material model for early-age cement-based materials

Cement-based support means such as the shotcrete lining and the jet-grouted soil become loaded in the course of the hydration process, requiring consideration of thermochemomechanical coupling in the analyses [3,4]. Within the material model accounting for these coupling effects, four dissipative processes are considered:

1. Hydration, resulting in chemical-shrinkage strains, aging elasticity, and strength growth.
2. Microcracking of hydrates yields plastic strains.
3. Stress-induced dislocation-like processes within the hydrates result in flow (or long-term) creep strains.
4. Stress-induced microdiffusion of water in the capillary pores between the hydrates result in viscous (or short-term) creep strains.

All material properties are related to the degree of hydration [3] by intrinsic material functions. The respective material functions for shotcrete and jet-grouted soil can be found in [4].

3. Presentation of results

As an example problem, a tunneling situation characterized by low overburden is chosen. The surrounding soil is modeled as a homogeneous material consisting of either medium-dense sand or soft clay (see Table 1). With regards to these ground conditions, a three-step excavation scheme consisting of top heading, benches, and invert is considered in the numerical simulation. After each excavation step, application of shotcrete on to the tunnel walls is simulated by changing the material description from soil to shotcrete in the finite elements representing the lining. Additionally, ground improvement by means of horizontal jet grouting (HJG) is considered[i] (Fig. 1). The properties of jet-grouted soil depend on the amount of injected cement grout, which depends on the in-situ soil. In case of granular material, the cement grout mixes with the soil particles, giving mechanical properties close to those of mortar ($f_{c,\infty}$ and E_∞ were set equal to 8 MPa and 1500 MPa, respectively). During jet grouting in clays, on the other hand, the soil is almost replaced by the injected cement grout. Accordingly, in this case both the compressive strength f_c and Young's modulus E at the end of hydration ($t = \infty$) were set equal to the respective values of cement paste, i.e. $f_{c,\infty} = 2.5$ MPa and $E_\infty = 550$ MPa.

Altogether, four numerical simulations were performed, covering tunnel excavation with and without HJG in medium-dense sand and clay. Based on the obtained numerical results, the following questions arising from the application of different support means in NATM tunneling in different geological conditions are addressed:

Does the local destruction of the soil microstructure during jet grouting result in settlements that finally, after tunnel excavation, give larger settlements compared with tunnel excavation without ground improvement?

Standardly, the construction of the jet-grouted support is optimized in order to minimize these pre-excavation settlements by avoiding fresh-to-fresh jet-grouted columns [4]. It has been shown that the horizontal dimension of the jet-grouted support defines the amount of settlements associated with the ground-improvement work [5]. In certain cases, limitation of ground improvement to the benches, characterized by a rather small horizontal dimension of the jet-grouted support, yields fewer total settlements (resulting from jet grouting *and* excavation) than the tunnel excavation

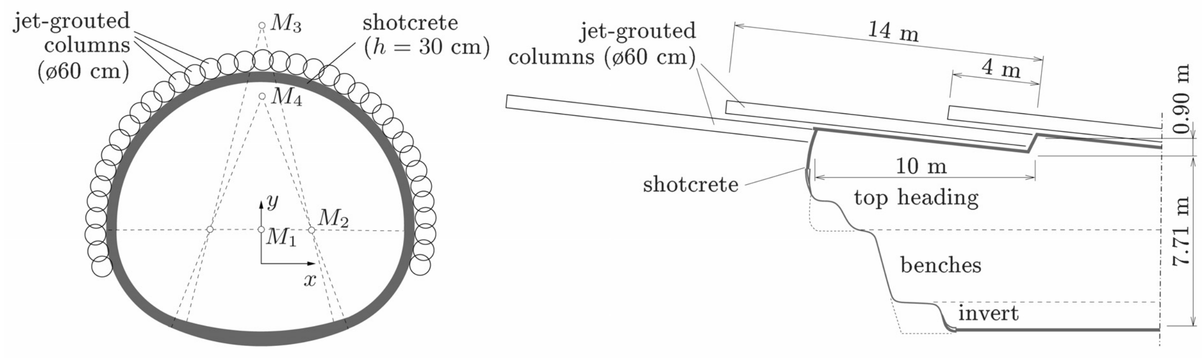

Fig. 1. Adopted tunnel excavation situation.

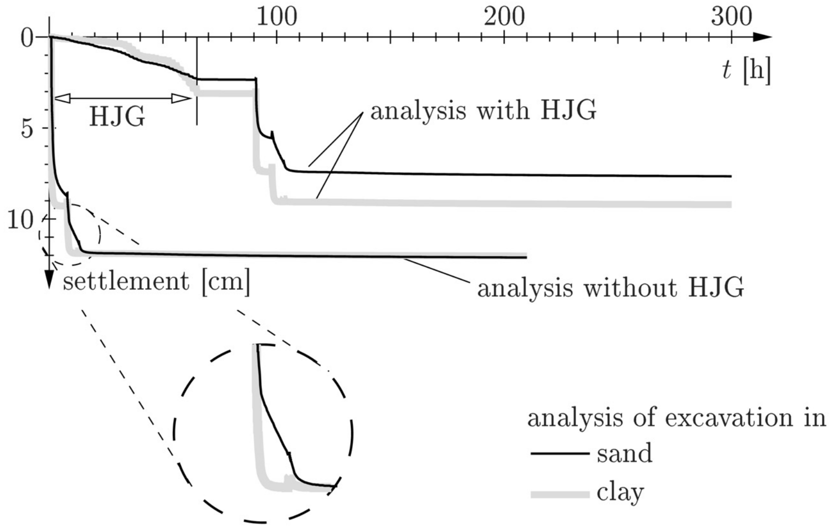

Fig. 2. History of surface settlements above crown.

supported by an entire jet-grouted support ring. In the present study, where a support ring consisting of 37 columns was considered, the settlements associated with ground improvement amounted to 23 mm and 31 mm for jet grouting in sand and clay, respectively. The higher settlements for the clay, especially when jet grouting near the top heading is performed (for the construction scheme of the jet-grouted support, see [4]), can be explained by the higher dead load of the clay (see Table 1) and the lower inital strength and stiffness of the early-age jet-grouted clay.

Even though the final settlements obtained from the analyses disregarding jet grouting, taking only the interaction between the creeping soil and the hydrating shotcrete lining into account, are almost equal[ii], the settlements obtained from the analyses considering HJG are quite different (Fig. 2). On the one hand, this difference is explained by the different mechanical properties of jet-grouted clay and sand. On the other hand, as will be described later, inelastic deformations in the soil adjacent to the jet-grouted support lead to different deformation patterns of the tunnel opening, yielding less convergence and higher settlements for the tunnel excavation in clay.

Compared with tunnel excavation considering a shotcrete support only, HJG led to a reduction of the final settlements by 33% in sand and by 25% in clay, justifying the application of ground-improvement techniques within the considered three-step excavation scheme, especially for tunneling in urban areas.

How do support means influence the convergence history measured on site, and does the latter provide insight into the structural performance of the support means?

As mentioned earlier, adaptation of support means in NATM tunneling is based on in-situ measurements. Hence, the question of how the obtained measurements change when new structural components such as jet-

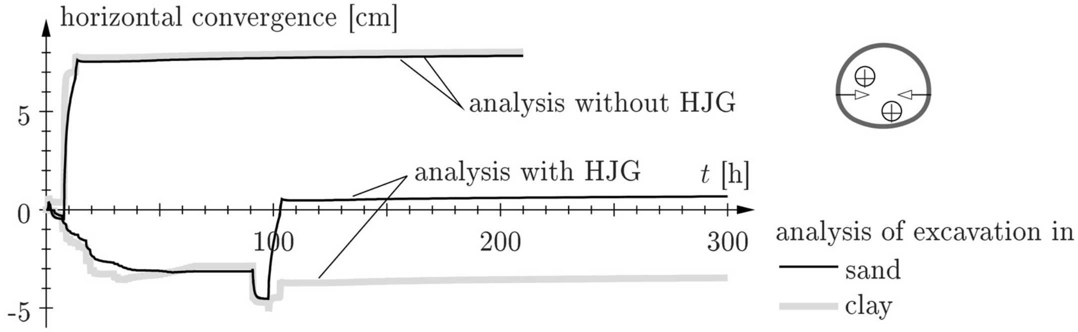

Fig. 3. History of horizontal convergence.

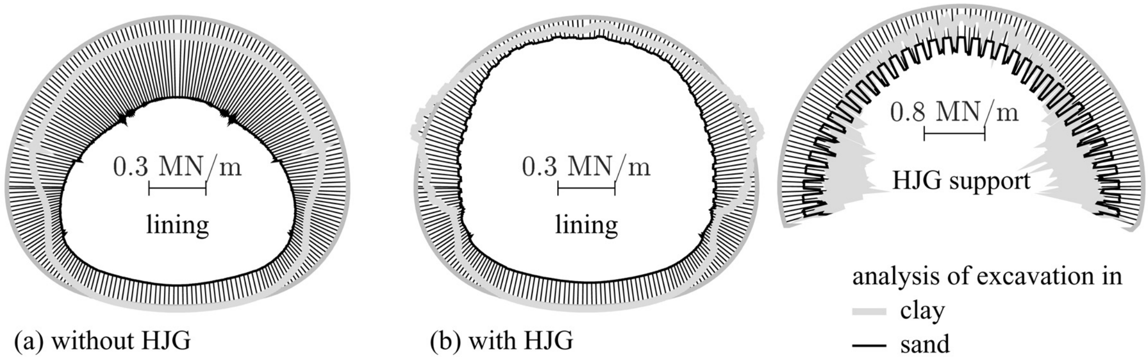

Fig. 4. Distribution of hoop force (a) in the lining when HJG is disregarded, and (b) in the lining and the jet-grouted support when HJG is considered (plots give hoop force seven days after excavation of the invert).

grouted support are introduced is of prime interest in the day-to-day decision process. Whereas the horizontal convergence depicted in Fig. 3 gives similar results for the analyses disregarding HJG, it differs significantly when jet grouting is taken into account. Focusing on the evolution of the horizontal convergence for $t > 91$ h (for $t < 91$ h, the convergence takes place in the improved ground and, hence, cannot be accessed on site), the structural support provided by the jet-grouted support ring led to a reduction of the convergence. Whereas the dilation associated with direction of plastic flow of the Mohr–Coulomb criterion still leads to convergence during tunnel excavation, the confined compressive stress states in the clay close to the jet-grouted support at the benches result in compaction (the associative flow rule was adopted for the Cam–Clay criterion), yielding a further decrease of the convergence.

How do the geological conditions and support means influence the loading characteristics of the soil-support composite structure?

Whereas similar values for the final settlements were obtained for both types of soil in the analyses disregarding HJG, the loading of the shotcrete lining is significantly different. Since the structural creep process in clay is considerably shorter (Fig. 2), the lining becomes loaded when the strength properties of shotcrete are less developed, resulting mainly in inelastic deformations. As the strength of the hydrating shotcrete lining increases with time, the creep process in the sand, which is significantly slower than that in clay, results in higher loading of the lining (Fig. 4a).

Application of HJG yields a composite-shell structure consisting of the jet-grouted support and the shotcrete lining. Accordingly, bending results in an increase of the hoop force in the shotcrete lining, while the hoop force drops in the jet-grouted support, and vice versa. This effect is more pronounced during tunneling in clay, where plastic compaction of the adjacent soil provides the flexibility required for bending, resulting even in tensile loading of the lining (Fig. 4b). As regards tunneling in medium-dense sand considering HJG, the confinement associated with plastic dilation preserves the compressive stress state in the lining. Because of this, the compressive hoop force in the lining for tunnel excavation in sand is greater in each shell section than the respective force obtained from tunneling in clay.

4. Concluding remarks

Based on the numerical analysis scheme employed in this paper, considering the complex construction process during NATM tunneling and accounting for the time-dependent behavior of the involved materials, the effect of support means in tunneling in different geological conditions was highlighted. However, the simulations were performed for specific time scales for the hydration process and for the viscoplastic behavior of soil. For a general study encompassing different time scales, the reader is referred to [2]. The numerical results presented in this paper indicated a strong influence of the time scale of the structural response – which, in addition to the material time scales, depends on the direction of plastic flow of the underlying failure criterion – on the loading of the support means. For example, even though similar settlements were obtained for tunneling in sand and clay, the loading of the lining was significantly different. Therefore, numerical studies are essential as regards information not accessible by measurements, such as the loading of the support means and, equally important, the effectiveness of the adaptation of support means. The latter provides (1) essential input for the day-to-day decision process at the construction site and (2) information on the changes in the displacement history that can be expected as the mode of adaptation has been specified.

Notes

[i] During HJG, slightly inclined holes drilled from the tunnel face are used for high-pressure injection of cement grout, finally giving a cone-shaped support ring consisting of cemented soil ahead of the tunnel face.

[ii] For both soils considered in this study, the time scales associated with creep were set equal. Accordingly, for a characteristic time τ for the sand equal to $\tau_{sand} = 0.15\,\mathrm{h}$, the viscosity η of the clay is obtained from $\tau_{\mathrm{clay}} = \eta_{\mathrm{clay}}/\tilde{\mathrm{E}}_{\mathrm{clay}} \overset{!}{=} \tau_{\mathrm{sand}}$, where $\tilde{\mathrm{E}}_{clay}$ is the Young's modulus for a stress state characterized by 20 m overburden and a lateral pressure coefficient of 0.5, giving $\eta_{clay} = 0.15 \times 20 = 3\,\mathrm{MPa\,h}$. However, in addition to the characteristic time τ for the creep process, the direction of plastic flow influences the time scale of the displacement history at the structural scale, e.g. the deformation in sand, where the plastic flow (dilation) deviates strongly from stress paths associated with confined compressive stress states, the structural response is significantly delayed (see Fig. 2). Thus, the almost-equal values for the final displacements in tunneling in sand and clay obtained from the analyses disregarding HJG are a coincidence rather than a consequence of the time scales for creep in soil, chosen to be equal for sand and clay (see zoom in Fig. 2).

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