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Optimisation of parameters for simulating a NATM tunnel in stiff clays based on a 3D model of exploratory adit

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Abstract

The paper presents comparison of 2D and 3D analyses of an exploratory adit of a NATM tunnel in stiff clays using two constitutive models (hypoplastic model for clays and Mohr-Coulomb model). The stress-release factor β of 2D simulation has been optimised to ensure that the 2D and 3D analyses give the same displecement field. The value of the β factor is, however, not unique to the given adit geometry, among other it dependends on the chosen constitutive model. The constitutive model parameters were subsequently optimised using monitoring data from the adit. Parameters of the hypoplastic model did not change substantially during the optimisation process. This model can therefore be used for predictions based on parameters calibrated solely on laboratory experimental data. The Mohr-Coulomb model gives correct predictions only for unrealistic model parameters and low K_0 values.

Keywords: Constitutive model, clay, tunnel, finite element method, inverse analysis

1 INTRODUCTION

The Dobrovského tunnels are the northern part of the large city ring road in Brno, the second biggest city in the Czech republic. The tunnels consist of two oval tunnel tubes with lengths 1237 m and 1258 m, respectively, with height of about 12 m, a section width of about 14 m and a full face area over 140 m^2. Both the tunnels are led parallel at a distance of 70 m and are being excavated by the NATM with vertical face sequence subdivided into 6 segments. The overburden ranges between 6 and 21 m. For exploration purposes, three adits were excavated in the direction of the twin-tube tunnel. The exploratory adits have approximately triangular cross sections with side length 5 m and are situated in the tunnel top headings (Fig.1).

Figure 1: Exploratory adits situated in the tunnel top heading and detail of the left drift excavation

The Brno area and the lot belong to the expanded pelagic Neogene of Carpathian fore-trough. Thickness of tertiary sediments reaches several hundreds of meters and lie directly on the crystalline rocks of the Brno massif. The natural cover of tertiary deposits is represented by Quartenary loess loams, clayey loams and sandy gravel. The pre-Quartenary base, in which the most part of the tunnel is excavated, is formed by Miocene limy, silty clay (Brno clay). The consistency of neogene clays is stiff, with a high plasticity.

As a part of the research work performed by the authors (Svoboda and Mašín [6]), the tunnel has been simulated using two different constitutive models (a hypoplastic model for clays and Mohr-Coulomb model) to compare their predictive capabilities. The approach chosen was as follows: First, the constitutive models were calibrated using experimental data on Brno clay and they were used in finite element simulations of exploratory adit. This allowed us to draw some conclusions on the predictive capabilities of the models based on parameters calibrated solely using laboratory data. Subsequently, the parameters were optimised using monitoring data from the exploratory adit and used for simulation of the full tunnel profile.

As the optimisation process of the model parameters is relatively demanding on the computer resources, it could not be performed based on a 3D model of exploratory adit. For this reason, the adit was simulated in 2D using the so-called β-method. In this method, the primary lining is activated after certain reduction of nodal forces along the tunnel boundary. The displacements predicted before the lining is generated represent ground displacements ahead of the tunnel face. The value of the factor β is difficult to estimate. It can be determined reliably only using direct comparison of 2D and full 3D numerical models. In their original contribution, Svoboda and Mašín [6] presented simulations of Dobrovského tunnel with a fixed value of the factor β=0.55. The aim of this paper is its proper evaluation by means of comparison 2D and full 3D finite element models of exploratory adit.

2 CALIBRATION OF CONSTITUTIVE MODELS

Two constitutive models were used in the simulations – an advanced non-linear hypoplastic model for clays by Mašín [2] and the basic Mohr-Coulomb model. Both the models were calibrated using the same experimental data on Brno clay. The experimental program consisted of oedometric and undrained shear tests (CIUP) on undisturbed Brno clay samples. In addition to the standard laboratory experiments, undrained shear tests with measurements of small-strain-stiffness using local LVDT gauges and bender elements were performed to provide enough information for calibration of the hypoplastic model also in the small-strain range. Parameters of the hypoplastic and Mohr-Coulomb models found on the basis of experimental data are summarised in Tab. 1.

Table 1: Parameters of the hypoplastic model (top) and Mohr-Coulomb model (bottom) calibrated using experimental data on Brno clay

φ_c	λ^*	κ^*	N	r	m_R	m_T	R	β_r	χ
19.9°	0.128	0.01	1.506	0.45	16.75	16.75	0.0001	0.2	0.8

φ	c	ψ	E	ν
28.5°	0 MPa	3°	8 MPa	0.4

3 MODEL OF THE EXPLORATORY ADIT AND DETERMINATION OF THE FACTOR β

The exploratory adit was simulated using finite element software *Tochnog Professional*. The implementation of the constitutive models used is freely available on the web, see Gudehus et al. [1]. The problem geometry and finite element mesh consisting of 4680 8-noded brick elements is shown in Fig. 2. The 2D mesh used is equivalent to the cross-section of the 3D mesh perpendicular to the adit axis. The bottom 27.7m thick strata represent the Brno clay and it has been simulated using parameters from Tab. 1. The overlying layers of loams and gravels were simulated using the Mohr-Coulomb model. The shotcrete lining was in the 3D model simulated as a linear elastic material with time dependent stiffness with the same parameters as used by Mašín [3]. The adit excavation was simulated as undrained with reduced bulk modulus of water [3].

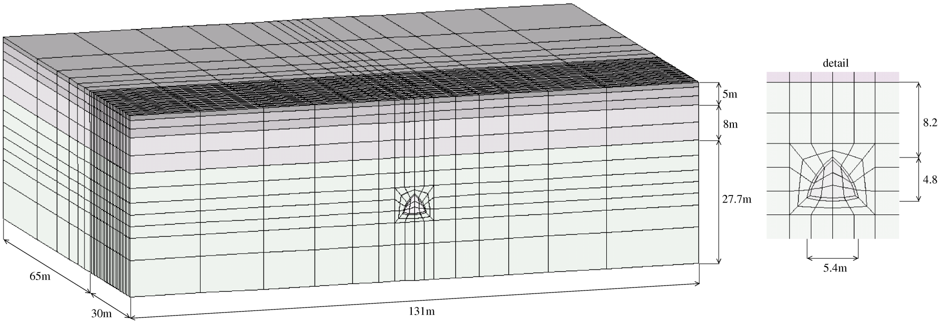

Figure 2: Geometry and finite element mesh of the 3D model of exploratory adit.

As there is no direct measurement of the K_0 state in the Brno clay, two values of K_0 were considered in simulations. One corresponds to normally consolidated conditions according to Jáky formula (K_0 = 0,66), the second corresponds by Mayne and Kulhawy [4] to the apparent overconsolidation of the soil specimens measured in the oedometric apparatus (K_0 = 1,25).

The β factor of the 2D analyses was optimised by means of an inverse analysis using a modified Gauss-Newton method performed using an open-source software UCODE [5] to ensure that the 3D and equivalent 2D analyses predict as closely as possible the surface settlement trough.

The values of the β factor found by means of the optimisation process are summarised in Table 2. The β factor depends on the selected constitutive model and it is not substantially influenced by the K_0 value. This shows that care must be taken when selecting the β factor solely based on experience without equivalent 3D modelling of the tunnelling process.

Table 2: Values of the factor β for different K_0 conditions and different constitutive models

Constitutive model	K_0	β
hypoplasticity	1.25	0.495
	0.66	0.467
MC model	1.25	0.594
	0.66	0.551

Figure 3 shows surface settlement troughs and Figure 4 shows displacement field around the adits predicted by the 3D simulations and equivalent 2D simulations with optimised values of the β factor. When appropriate values of the β factor are selected, the 2D analysis gives results equivalent to the 3D analysis with few slight differences. The Mohr-Coulomb model with $K_0 = 1{,}25$ gives in 2D wider settlement trough than in the 3D. Also, the 2D analysis predicts larger heave of the adit bottom than the 3D analysis.

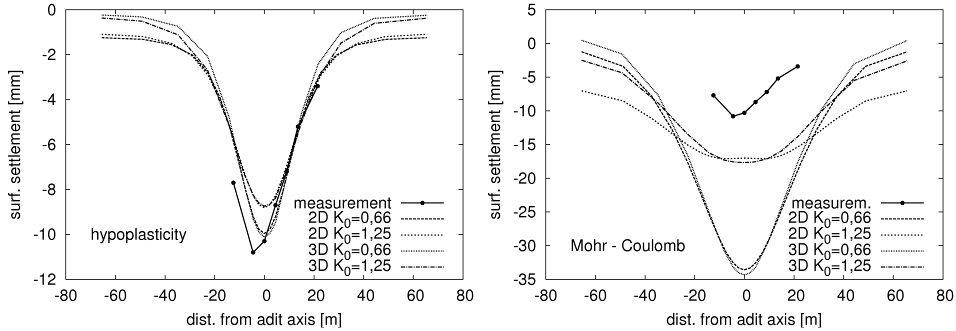

Figure 3: Comparison of the surface settlement troughs predicted by the 3D models and by the 2D models with optimised values of the factor β.

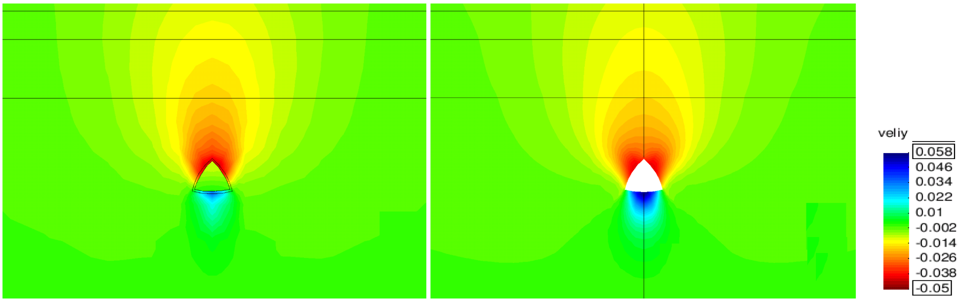

Figure 4: Comparison of vertical displacement field predicted by the 3D model (left) and 2D model with optimised value of the factor β (right) using the hypoplastic model.

4 OPTIMIZATION OF MODEL PARAMETERS USING MONITORING DATA

The 2D analyses with appropriate values of the β factor found on the basis of 3D simulations were used in a further study of the adit behaviour. Figure 3 demonstrates that the hypoplastic model gives a good estimate of the settlement trough shape and magnitude already with the model parameters calibrated using laboratory data. The Mohr-Coulomb model highly overestimates settlement magnitude and for high K_0 it also predicts unrealistic (too wide) settlement trough shape.

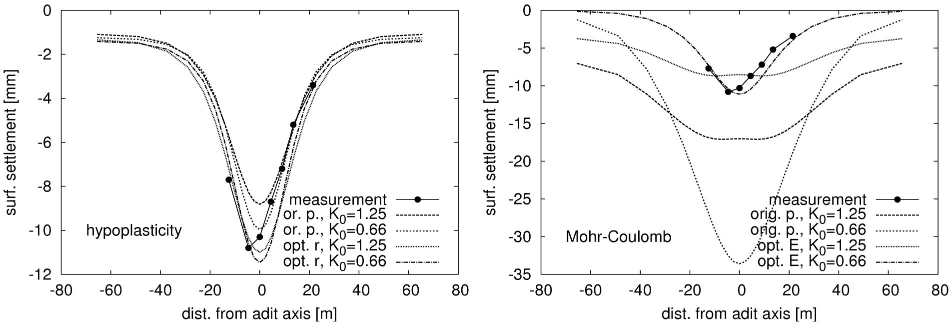

Figure 5: Surface settlement troughs from the 2D FE simulations predicted with the original and optimised parameter sets.

Results in Fig. 3 were produced with parameters calibrated using small-size laboratory experiments. It is reasonable to expect, that due to the size-effects, the parameters appropriate for simulation of the large-scale boundary value problem may differ slightly from parameters obtained from laboratory experiments. For this reason, the constitutive model parameters were optimised using the same procedure, as used for the optimisation of the β factor, to reproduce as closely as possible the measured surface settlement trough. Only the parameters controlling the shear stiffness (*r* for hypoplasticity and *E* for the MC model), which have the most pronounced effect on the results of the analyses, were optimised.

Table 3: Original and optimised values of selected constitutive model parameters.

Constitutive model	K_0	Orig. value	Optim. value
Hypoplasticity (parameter r)	1.25	0.45	0.511
	0.66		0.493
MC model (parameter E)	1.25	8 MPa	18.88 MPa
	0.66		56.23 MPa

Tab. 3 gives original and optimised values of parameters and Fig. 5 shows the surface settlement troughs predicted with the two parameter sets. The parameter values did not change significantly in the case of a hypoplastic model. On the contrary, the Young modulus *E* of the Mohr-Coulomb model had to be changed significantly in order to reproduce the measured settlement profile. Unlike hypoplasticity, predictions by the Mohr-Coulomb model could be optimised successfully for the low value of K_0 only, for high K_0 the model gives unrealistically wide settlement trough and these predictions cannot be improved by varying the value of *E*.

5 CONCLUSIONS

The main aim of the present paper was to present comparison of 2D and fully 3D analyses of an exploratory adit of a NATM tunnel, which is recently being built in the Czech Republic. It was shown that the β factor, used in 2D analysis of NATM tunnelling to incorporate the 3D effects, can be optimised in such a way that the 2D and equivalent 3D analysis give the same displacement field around the tunnel. The value of the β factor is, however, not unique to the given adit geometry. It depends on the chosen constitutive model. The influence of the K_0 value is not significant.

The constitutive model parameters were subsequently optimised to ensure that the 2D analyses predict surface settlement troughs in agreement with monitoring data. The hypoplastic model can be used successfully for predictions based solely on laboratory experimental data (the original and optimised parameter values do not differ substantially); the Mohr-Coulomb model requires unrealistic parameters to reproduce the measured behaviour and in the case of high K_0 the surface settlement trough shape is unrealistic (too wide) even for optimised parameter set.

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