IMPACT OF A CONSTITUTIVE MODEL ON INVERSE ANALYSIS OF A NATM TUNNEL IN STIFF CLAYS

Tomáš Svoboda, David Mašín
Charles University, Faculty of Science, Czech Republic
tsvoboda@centrum.cz, masin@natur.cuni.cz

SYNOPSIS

The paper demonstrates the influence of soil constitutive model on predictions of a NATM tunnel in overconsolidated clays (Dobrovského tunnel, Brno, Czech Republic). Two constitutive models are compared: standard Mohr-Coulomb model and advanced hypoplastic model. The models have been calibrated using laboratory experimental data. Their parameters have subsequently been optimised by means of inverse analysis using monitoring data from exploratory adit, excavated inside the future tunnel. The hypoplastic model gives reasonable predictions of the adit behaviour even with parameter set calibrated using experiments. The Mohr-Coulomb model requires unrealistic parameters to predict the adit behaviour correctly. The optimised parameters are used for calculation of settlements due to the tunnel. Although both the models with optimised parameter sets give comparable predictions of settlements due to the adit, predictions of the behaviour of the whole tunnel differ substantially. Predictions by the hypoplastic model appear to be more reasonable, but detailed conclusions cannot be drawn yet. They will be available after excavation of the whole tunnel in 2009.

1. INTRODUCTION

The increasing traffic in Brno, one of the largest cities in the Czech Republic, contributed to decision that the historical centre should be relieved from traffic by construction the large city ring road (LCRR). The Dobrovského tunnel, which is scope of this study, is the northern part of the LCRR. The tunnel consists of two oval tunnel tubes with lengths 1237m and 1258m, respectively, with height of about 12m, a section width of about 14m and a full face area over 140m^2. Both the tunnels are led parallel at a distance of 70m and are being excavated by the NATM with vertical face sequence divided into 6 segments. The overburden ranges between 6 and 21m. 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 5m and are situated in the tunnels top heading (see Fig.1). The adits were aimed at engineering-geological and hydrogeological conditions verification, to check the proposed excavation technology and to determine the impact of excavation on neighbouring buildings. Consequently, they were used as a part of final full face cross section.

In this paper we present numerical analyses of the Dobrovského tunnel. Two different material models for Brno clay are compared. The procedure followed in the analyses is as follows: (1) calibrate selected constitutive models using laboratory experimental data on Brno clay; (2) simulate the behaviour of exploratory adit and optimise the parameter sets by means of inverse analysis using adit monitoring data and (3) simulate the whole tunnel using optimised parameter sets. The paper demonstrates advantages of advanced constitutive models in predictions of geotechnical problems.

2. GEOLOGICAL CONDITIONS

From the stratigraphic view the Brno area belongs to the expanded pelagic Neogene of Carpathian fore-trough. Thickness of tertiary sediments reaches several hundreds of meters and lie directly on crystalline rocks of the Brno massif. The tunnel itself is situated in the center of town Brno, hence the significant portion of surface is urbanized and a free area is covered with backfills. The natural cover of tertiary deposits is represented by Quatenary loess loams containing rounded calcite concretions, sedimented by eolic activity in Pleistocene. The underlying clayey loams having mixed eolic-diluvial origin are rainwater re-deposited layers with variable thickness.The basis of Quatenary cover is constituted by sandy gravel often with loam and clay mixture. The occurence of the this layer is not continuous.

The pre-Quartenary base, in which the tunnel is excavated, is in the investigated area formed by Miocene lower Badenian ground. From the engineering-geological point of view it is limy, silty clay (Brno clay). The consistency of neogene clays is stiff, locally hard, the plasticity is high. A non-altered ground has green-gray color. In proximity of the surface an altered clay has yellow brown to rusty brown color (see Fig.1). It is caused by limonitical solutions penetrating the lightly weathered clay massif through a system of discontinuits and faults. The significant and continuous faults are slickensided, grooved in a movement direction.

(a) *(b)*

Fig.1 Exploratory adits situated in the tunnel top heading (a), left drift excavation with boundary of altered and non-altered Brno clay (b)

3. LABORATORY EXPERIMENTS

Mechanical behaviour of a Brno clay, in which the tunnel is excavated (see Fig. 5), was studied thoroughly by means of high-quality laboratory experiments. Samples from two boreholes (borehole for extensometer monitoring abbreviated as "EXT" and borehole for inclinometer monitoring abbreviated as "INC") next to the tunnel cross-section were used in the investigation. Three undisturbed samples were taken from each borehole from different depth levels (15.5 and 19.5 m respectively) using thin-walled samplers. Experimental results are presented together with model simulations in Sec. 4. Mechanical behaviour of Brno clay has been studied only. As demonstrated in Sec. 5, behaviour of loess loams and sandy gravels does not have significant effect on predicted tunnel performance.

Three undrained triaxial tests on each sample were performed. The triaxial specimens were of the diameter of 38 mm. Standard platens were used without any measures to reduce end friction, all samples were equipped with radial drainage in order to speed up the pore pressure dissipation. All triaxial specimens were isotropically consolidated up to different stress levels (approx. 250, 500 and 750 kPa) and then sheared with constant axial strain rate. The specimens were equipped with submergible local LVDT axial strain transducers in order to evaluate soil stiffness in the small strain range. In addition, one specimen was equipped with bender elements – piezoceramic platens that are used for measurement of soil stiffness in the very small strain range by means of propagation of shear waves.

In addition to triaxial tests, oedometric tests have been performed on undisturbed and equivalent reconstituted specimens. The specimens were loaded up to high axial pressures (13 MPa) in order to fix the position of normal compression line and in order to evaluate the overconsolidation ratio, which is used for estimation of the coefficient of earth pressure at rest K_0. Finally, a set of ring-shear tests on reconstituted specimens has been performed. Following [11], peak friction angle on normally consolidated reconstituted specimens evaluated in ring-shear apparatus is considered to be appropriate estimation of the critical state friction angle of soil, which is difficult to be estimated reliably using triaxial tests on undisturbed specimens due to strain localisation into shear bands.

4. CONSTITUTIVE MODELS AND THEIR CALIBRATION

In this work, results by two constitutive models used for modelling of Brno clay are compared. First model used is a standard Mohr-Coulomb model. This model has been selected as in the Czech Republic it is still the most popular model used in numerical analyses in geotechnical engineering.

The second model is a hypoplastic model for clays [1,2,3] enhanced by the intergranular strain concept [4]. This model has been chosen as a representative example of advanced constitutive models for soils. The model can take into account features of soil behaviour important for correct predictions of deformation field due to tunnelling, namely non-linearity of soil behaviour, high quasi-elastic stiffness in the very small strain range and stiffness degradation with strain. Implementation of the model is freely available at www.soilmodels.info site (see [5]).

The basic version of the hypoplastic model requires five soil parameters, equivalent to parameters of the Modified Cam clay model: *N,* λ^*, κ^*, φ_c and *r*. Parameters *N* and λ^* define position and slope of the isotropic normal compression line in the ln *p* vs. ln (1+*e*) plane, where *p* is mean stress and *e* is void ratio. Parameter κ^* defines slope of the isotropic unloading line in the same plane. Calibration of these three parameters using oedometer data on undisturbed Brno clay sample is shown in Fig. 2.

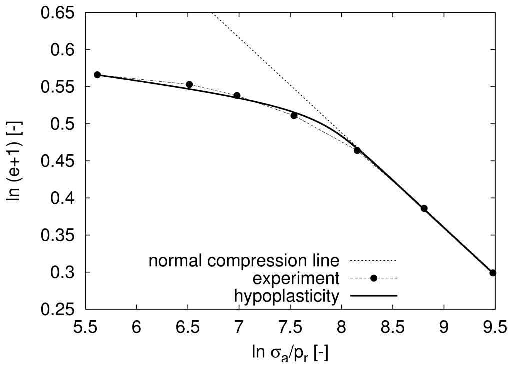


Fig.2 Calibration of parameters N, λ^* and κ^* of the hypoplastic model using edometer test data on undisturbed sample

Parameter φ_c is a critical state friction angle. It has been calibrated using ring shear tests on reconstituted specimen, as discussed in Sec. 3. Finally, parameter *r,* which controls the shear stiffness, has been found using data from undrained triaxial tests on undisturbed sample (Fig. 3). Figure 3a shows deviatoric stress vs. shear strain curves, Figure 3b undrained stress paths.

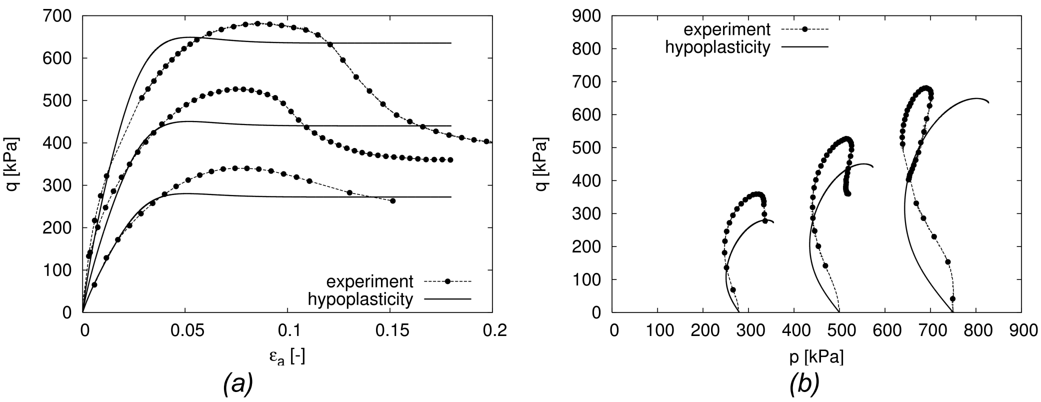


Fig.3 Calibration of parameter r of the hypoplastic model and simulations of undrained test data on undisturbed Brno clay samples

The basic hypoplastic model is capable of predicting the soil behaviour in the medium to large strain range. In order to predict high quasi-elastic stiffness and stiffness degradation in the small strain range, it is enhanced by the intergranular strain concept [4]. The enhanced model requires five additional parameters (m_R, m_T, R, β_r and χ). These parameters are found using shear stiffness measurements by means of bender elements and local axial strain transducers (for details see [4,1]). Measurement of quasi-elastic stiffness by bender elements and model predictions are shown in Fig. 4a, predictions of stiffness degradation curve measured using local axial strain transducers in Fig. 4b.

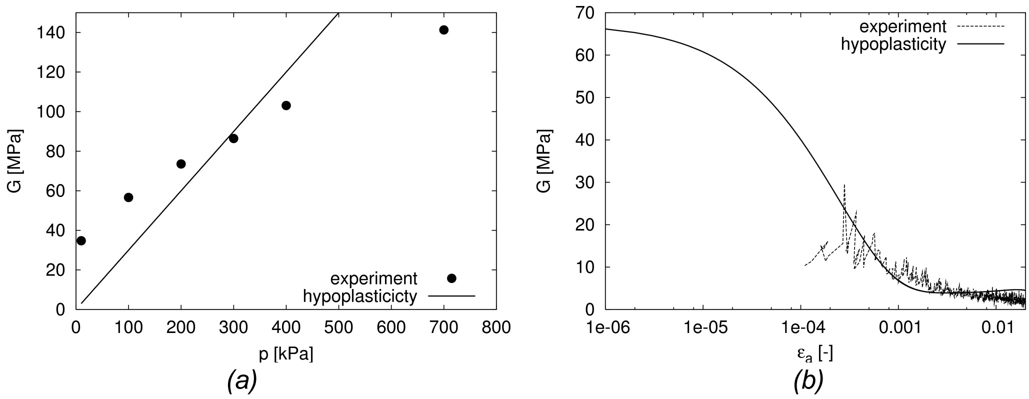


Fig.4 Shear stiffness of undisturbed Brno clay in the very small and small strain range predicted by the hypoplastic model

Parameters of the hypoplastic model calibrated using experimental data are given in Tab. 1. Calibration of the Mohr-Coulomb model cannot be detailed due to the space restrictions. Parameters of the Mohr-Coulomb model calibrated using the same experimental data as the hypoplastic model are given in Table 2.

Tab.1 Brno clay parameters of the hypoplastic model calibrated using experimental data

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

Tab.2 Brno clay parameters of the Mohr-Coulomb model calibrated using experimental data

φ	c	ψ	E	ν
28.5°	0 MPa	3°	8 MPa	0.4

5. SIMULATION OF EXPLORATORY ADIT

As indicated in the Introduction, first step in the analyses presented was simulation of the exploratory adit, which has been built on site in advance of the tunnel in order to check the geological conditions and response of the soil to tunnelling. The problem has been solved by 2D finite element method using software Tochnog Professional.

Problem geometry, finite element mesh (composed of 336 9-noded quadrilateral elements) and geological cross-section are shown in Fig. 5. The geometry corresponds to cross-section numbered at the site T2-0.840. Side-length of the exploratory adit is approx. 5 meters, its top is situated 21.2 m below ground level. Ground water table is located at the top of the Brno clay strata. Groundwater flow has been taken into account in the analyses (coupled consolidation analyses were performed), with permeability $4.8 * 10^{-8}$ m/s. Permeability was measured using *in situ* tests and evaluated from granulometry using empirical relationships. Time required to excavate the whole tunnel was 8 days. 3D effects have been taken into account by the so-called β–method (see, e.g., Karakus [6]). The nodal forces along the tunnel geometry are reduced by the factor β before the primary lining is installed. This reduction aims at simulating displacements of the soil massif in advance of the tunnel face. In the simulations, value of β equal to 0.55 has been used.

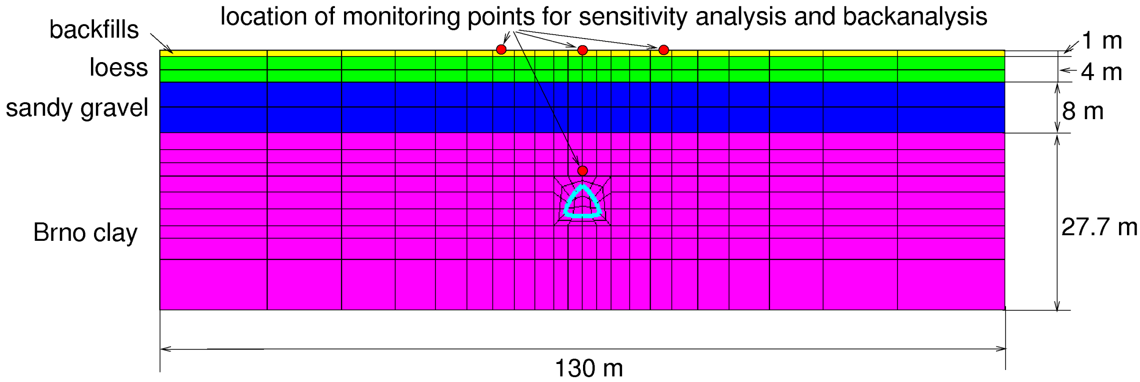


Fig.5. Problem geometry and finite element mesh used in simulations of the exploratory adit

In addition to material properties of Brno clay, it was necessary to specify parameters of soil layers above the clay strata (see Fig. 5). All the three layers have been simulated using Mohr-Coulomb model with parameter sets according to Czech standards and from commercial investigations in shear box apparatuses. These parameters are given in Table 3.

Tab.2 Parameters of the soil layers above Brno clay

soil	φ [°]	*c* [MPa]	ψ [°]	*E* [MPa]	ν
backfill	20	10	4	10	0.35
loess	28	2	2	45	0.4
sandy gravel	30	5	8	60	0.35

Lining has been modelled as linear elastic material using truss-beam elements with material properties given in Table 3.

Tab.3 Parameters of the primary lining of exploratory adit and of the final tunnel

lining	Young modulus E [MPa]	Eq. thickness [m]	density [kg/m3]
adit	24.6	0.1	2970
tunnel	24.6	0.35	2970

Initial conditions of the simulation consisted of prescribing the vertical stresses, void ratio and coefficient of earth pressure at rest K_0. Vertical stresses were calculated through the soil unit weight γ equal to 18.5 kN/m^3 for Brno clay, 19.1 kN/m^3 for loams and sandy gravel and 17.7 kN/m^3 for the backfill (values correspond to Czech standards). Initial void ratio of Brno clay has been measured on undisturbed samples from the two boreholes. e=0.83 has been used in simulations. Value of K_0 has been estimated using empirical relationship by Mayne and Kulhawy [7]:

$$K_0 = (1 - \sin\varphi) OCR^{\sin\varphi} \tag{1}$$

Overconsolidation ratio OCR has been estimated from oedometric test on undisturbed Brno clay sample (see Fig. 2). The preconsolidation pressure is approximately 1800 kPa, which leads to OCR in the tunnel depth equal to 6.5 and to K_0=1.25. Simulation results of the exploratory adit using initial set of parameters are presented later in Sec. 7.

6. SENSITIVITY ANALYSIS

In order to clarify the influence of the soil layers above Brno clay strata on the results of simulations, sensitivity analysis has been performed. Sensitivity analysis, as well as backanalysis presented in Sec. 7, has been perfomed using software UCODE [8].

In the sensitivity analysis and backanalysis results of simulations have been compared with measurement of vertical displacements at four locations, as indicated in Fig. 5. Three locations are located at the surface, displacements were measured by means of geodetic survey. The fourth monitoring point is located just above the adit crown. Measurements were performed by means of extensometers. Difference between simulation and monitoring data were expressed in terms of an *objective function S(b)* (e.g., [9]) which takes the form:

$$S(b) = [y - y'(b)]^T \omega [y - y'(b)] \tag{2}$$

where b is a vector containing values of parameters, y is a vector of observations, $y'(b)$ is the vector of the computed values corresponding to the observations and ω is the weight matrix. The weight matrix evaluates significance of each measurement. Typically, weight of each observation is taken as the inverse of its error variance. In the present case with low number of observation used, however, each of the four observations is given the same weight equal to unity.

Sensitivity of results on variation of each of the paremeters may be evaluated in terms of *composite scaled sensitivity* css_j defined as

$$\mathrm{css}_j = \left[\frac{1}{ND} \sum_{i=1}^{ND} \left(\left(\frac{\partial y'_i}{\partial b_j} \right) b_j \omega_{ii}^{1/2} \right)^2 \right]^{1/2} \tag{3}$$

where b_j is the j-th parameter being studied, y'_i is the i-th computed value, $\partial y'_i / \partial b_j$ is sensitivity of the i-th computed value with respect to j-th parameter, ω_{ii} is weight of the i-th observation and ND is number of observations.

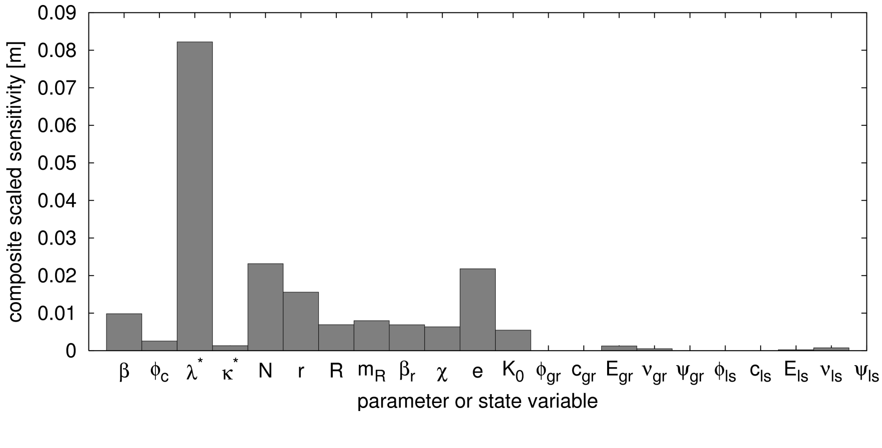


Fig.6. Composite scaled sensitivities for simulations of exploratory adit, 4 observation values from Fig. 4, Brno clay modelled using hypoplastic model.

Composite scaled sensitivities for simulation of exploratory adit using observation values from Fig. 5 and with Brno clay modelled using hypoplastic model are given in Fig. 6. Parameters without any subscript are hypoplastic parameters of Brno clay, subscript *ls* refers to loess strata and *gr* to sandy gravel strata (see Fig. 5). In addition to model parameters, Fig. 6 includes also sensitivity of results to change of state variables *e* (void ratio) and K_0 and to change of the β factor (see Sec. 5).

Figure 6 clearly shows that the results are primarily sensitive to parameters of the Brno clay strata, parameters of loess and sandy gravel do not influence the results substantially. For this reason, mechanical behaviour of these two layers have not been studied in detail. These layers are in all subsequent simulations simulated using Mohr-Coulomb model with parameters according to Tab. 2.

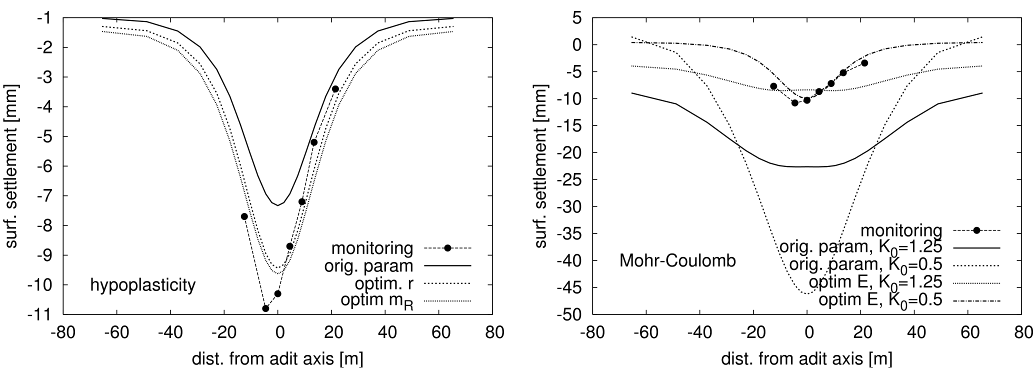
7. INVERSE ANALYSIS OF PARAMETERS USING DATA FROM EXPLORATORY ADIT

It is a common problem of investigation of soil behaviour in geotechnical practice that laboratory specimens due to size effects often do not represent accurately the behaviour of the whole soil massif. For this reason, soil parameters calibrated by means of laboratory experiments (Sec. 4) have been corrected by means of inverse analysis of exploratory adit. The corrected parameters are in Sec. 8 used for class A predictions of deformations due to the whole tunnel. The inverse analysis has been performed using software UCODE (see Sec. 6). In the inverse analysis, parameter values and other aspects of the model are automatically adjusted until the model's computed results match the observed behaviour of the system [9]. UCODE performs optimisation by means of minimalisation of the objective function *S(b)* (Sec. 6, Eq. (2)) using modified Gauss-Newton method. In the analyses presented, vertical displacements from four locations indicated in Fig. 5 are used to assemble the objective function *S(b)*.

As demonstrated in many detailed studies (see, e.g., [10]), deformations due to NATM (sprayed concrete) tunnelling in fine-grained soils are the most significantly influenced by soil stiffness and its non-linearity. For this reason, parameters of the hypoplastic model controlling the shear stiffness (namely r and m_T) have been optimised. In the case of the Mohr-Coulomb model, parameter controlling the soil stiffness, which has been optimised, is Young modulus E.

Figure 7a shows surface settlement trough due to the exploratory adit calculated using hypoplastic model, Figure 7b shows the same for Mohr-Coulomb model. Hypoplastic model with original parameter set calibrated using laboratory data (Sec. 4) underesimates by approximately 30% settlement magnitude, and the shape of the settlement trough is predicted correctly. Mohr-Coulomb model overestimates surface settlements by approx. 100% and it predicts unrealistically wide settlement trough. As results by Mohr-Coulomb model are sensitive to the value of K_0, simulations for unrealistically low K_0=0.5 are also included in Fig. 7b. With the original parameter set the shape of the trough predicted by the Mohr-Coulomb model is reasonable, but it overpredicts settlement magnitude by 450 %.

Figure 7 shows also surface settlements predicted by the two models with optimised parameter sets (Tab. 4 and Tab. 5). Optimisation of hypoplastic parameters r and m_R has approximately the same effect on results, surface settlement trough with optimised parameters has shape corresponding to the monitoring data (even though the K_0 value is equal to 1.25) and also settlement magnitude is predicted correctly. Settlement trough for Mohr-Coulomb model with realistic K_0 is too wide. Only with K_0=0.5 the Mohr-Coulomb model predicts correctly both the trough shape and settlement magnitude.



(a) (b)

Fig.7. Simulation of the settlement trough due to the exploratory adit with original parameter set (calibrated using laboratory data) and optimised parameters.

Note that correct predictions by the Mohr-Coulomb model were achieved only with unrealistically high value of Young modulus (Tab. 5), and unrealistically low value of K_0. Therefore, unlike the hypoplastic model, which performed reasonably even with original parameter set, the Mohr-Coulomb model cannot be used for predictions of the settlement due to the tunnelling based solely on laboratory experimental data. Its capability to be used for prediction of tunnel performance through inverse analysis of parameters is studied in Sec. 8.

Tab.4 Initial and optimised values of parameters r and m_R of the hypoplastic model

parameter set	r	m_R
original param.	0.45	16.75
optimised r	0.515	16.75
optimised m_R	0.45	12.42

Tab.5 Initial and optimised values of parameter E the Mohr-Coulomb model for different K_0 values.

parameter set	E [MPa]
original param.	8
opt. E, K_0=1.25	24.2
opt. E, K_0=0.5	148.9

8. CALCULATION OF SETTLEMENT DUE TO THE TUNNEL

Original parameter sets and parameter sets optimised by inverse analysis using exploratory adit data (Sec. 7) have been used for predictions of the behaviour of the whole tunnel. Unlike exploratory adit, the tunnel has not been built yet (it is expected cross the simulated monitoring section during 2009). Presented results therefore represent class A predictions of the tunnel performance. Their comparison with the observed tunnel behaviour will be done is subsequent publications.

The tunnel has been simulated using the same method as the exploratory adit, i.e. β-method in 2D coupled consolidation finite element analysis. Problem geometry is shown in Fig. 8. The tunnel width is approx. 14.5 m, its top is located 20 m below the ground surface. Excavation of the tunnel is done using sequential method. Sequence of excavation is demonstrated in Fig. 9, which also shows development of vertical settlements as simulated by the hypoplastic model with optimised parameter *r*.

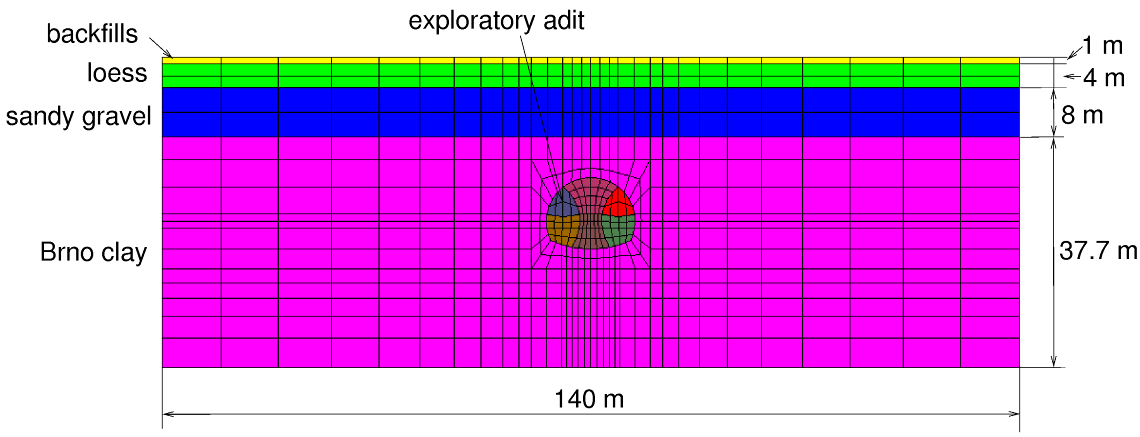


Fig.8. Problem geometry and finite element mesh used in simulations of the tunnel

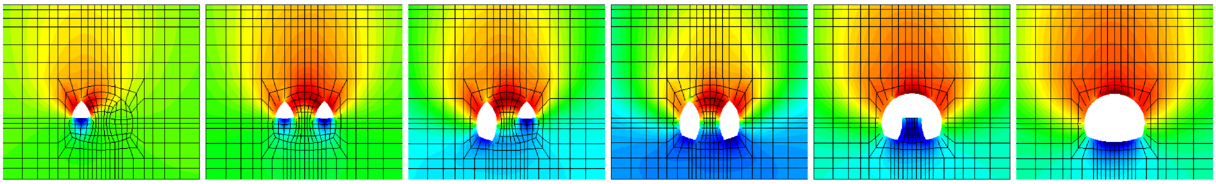


Fig.9. Excavation sequence of the tunnel and vertical displacements contours predicted by the r-optimised hypoplastic model. Different colour scale in different images.

Figure 10 shows surface settlement trough predicted by the studied constitutive models. Hypoplastic model, similarly to simulation of the exploratory adit, predict surface settlement trough of a reasonable shape. The *r*-optimised model predicts slightly deeper settlement trough, but the difference is not substantial. Significantly different predictions are obtained with the Mohr-Coulomb model. With the original parameters calibrated using laboratory data, the settlements predicted are unrealistic. The *E*-optimised model with K_0=1.25 gives similar settlement above the tunnel centreline as the hypoplastic model, but the settlement trough is too wide. The *E*-optimised model with K_0=0.5 predicts much deeper settlement trough than the hypoplastic model.

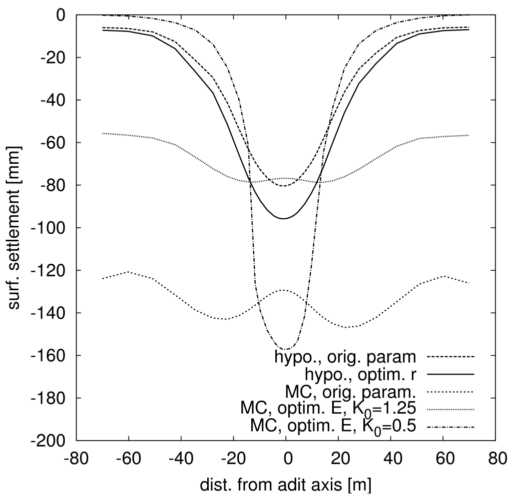


Fig.10. Surface settlement trough due to the whole tunnel predicted by the studied models

Figure 11 shows contours of vertical displacements around the tunnel predicted by the optimised models. Results correspond to Fig. 10. It is interesting to point out that the *E*-optimised Mohr-Coulomb model with K_0=0.5 predicts displacements close to failure state, in which the soil mass above the tunnel is moving downwards as a rigid block.

This section demonstrated that optimisation of different constitutive models using monitoring data from one geotechnical problem does not guarantee similar predictions of different problem in the same environment. The difference of predictions presented in this section is mainly due to the non-linear character of the hypoplastic model, and linear elastic stiffness predicted by the Mohr-Coulomb model. Strains are larger around the whole tunnel than around the exploratory adit. Stiffness of *E*-optimised Mohr-Coulomb model at K_0=0.5 using data from exploratory adit is unrealistically high (E=148.9 MPa). If the soil is subjected to larger strains, the stress state reaches the failure criterion and state close to failure is predicted (see Fig. 11). The non-linear hypoplastic model is expected to give more accurate predictions, as it predicts, in accordance with experimental data, gradual decrease of soil stiffness with strain level.

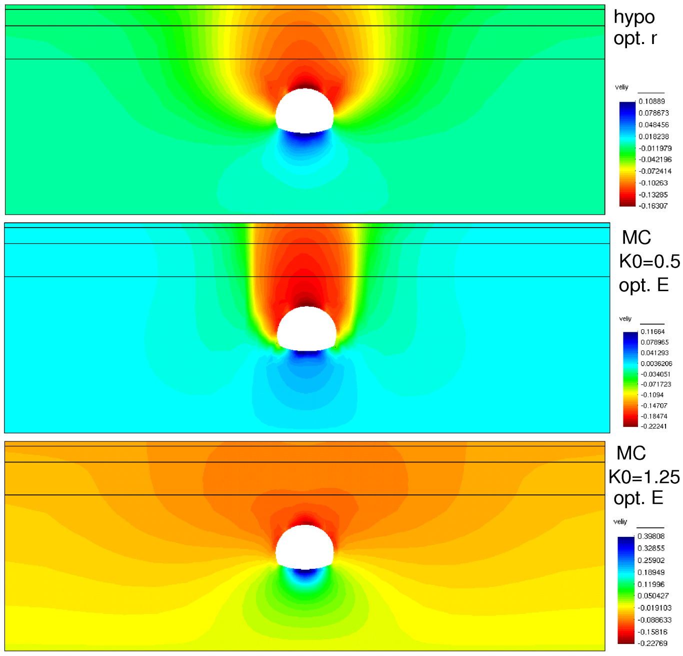


Fig.11. Vertical displacement field around the tunnel predicted by optimised hypoplastic and Mohr-Coulomb models.

9. CONCLUDING REMARKS

In the paper we have shown that selection of constitutive model used in numerical analysis significantly influences model predictions. Two models were compared – standard Mohr-Coulomb model and advanced hypoplastic model. It has been demonstrated using monitoring data from exploratory adit that the hypoplastic model predicts reasonable surface settlement even with parameters calibrated using laboratory data. This model can therefore be used for predictions of the geotechnical structure based solely on laboratory investigation. Mohr-Coulomb model predicts correctly the surface displacements caused by the exploratory adit only with unrealistic parameters (high value of Young modulus and low K_0) determined by inverse analysis. Still, the two models optimised using data from exploratory adit do not give the same predictions of the settlement trough caused by the whole tunnel. Predictions by the hypoplastic model appear to be more reasonable, but detailed conclusions cannot be drawn yet. They will be available after excavation of the whole tunnel in 2009.

10. ACKNOWLEDGMENT

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Mr. Tomáš Svoboda graduated in engineering geology from the Charles University in Prague in 2006. Since 2006 he has been a PhD student of the same university. In his MSc thesis he dealt with structural analysis of a Prackovice exploratory adit on highway D8, Czech Republic. In 2005 he was involved in structural analysis of a pilot tunnel on construction of Prague city ring road.

Dr. David Mašín graduated in engineering geology at Charles University in Prague in 2001, obtained M.Phil. degree in geotechnical engineering at City University in London and Ph.D. degree at Charles University in Prague. Since 2004 he has been a Senior Lecturer in numerical methods in geomechanics at Chares University, Prague. Among his professional interests belong soil mechanics, constitutive modelling of geomaterials and numerical modelling of boundary value problems in geotechnical engineering.