Evaluation of the earth pressure coefficient at rest by backanalysis of circular exploratory adit in Brno clay

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ABSTRACT: A numerical study aimed at investigating the earth pressure coefficient at rest K_0 is presented in the paper. An approach based on backanalysis of convergence measurements of underground cavity of circular cross-section is adopted to study K_0 of a stiff clay from Brno, Czech Republic. The models were developer using finite element method in 2D and in 3D. Both the models gave consistent results of K_0 equal approximately to 1.4. The model, however, does not consider stiffness anisotropy. The development of the new model is ongoing and the results will be precised in the forthcoming research.

1 INTRODUCTION

One of the most important quantities influencing results of numerical analyses of tunneling problems is the earth pressure coefficient at rest (K_0). Its importance in the predictions of tunneling problems has been demonstrated by number of authors.

As an example, Franzius et al. (2005) made a direct investigation into the influence of K_0 conditions in 3D FE analysis of a tunnel in London clay. He adopted two different values of K_0, namely $K_0 = 1.5$ and $K_0 = 0.5$. Low K_0 value (unrealistic for London clay) led to improved predictions, namely the normalized settlement trough was narrower and deeper. In absolute values, however, low K_0 induced overprediction of vertical surface settlements by a factor of 4. With $K_0 = 1.5$ the predicted trough was too wide and vertical displacements were underpredicted by the factor of 4.

Similar conclusions were drawn by Doležalová (2002) – decreasing the K_0 value from 1.5 to 0.5 closed up the settlement trough and increased vertical settlements in absolute terms.

Although the K_0 influences the simulation results significantly, it is in most cases unknown. In fact, although different field tests, laboratory-based measurements methods and numerical backanalysis procedures exist, none of them is flawless and they often lead to substantially different estimations. For a review of different approaches to K_0 estimation, see Boháč et al. (2013).

In this contribution, we discuss one particular approach to K_0 estimation, namely backanalysis of convergence measurements in an underground cavity. We demonstrate this approach using a case study from a stiff clay massif from the Czech Republic.

2 BRNO CLAY

The backanalysed adit is located in Brno clay, within the town of Brno, Czech Republic. The Brno clay (“Tegel”) is of Miocene (lower Badenian) age and belongs to the Neogene of Carpathian foredeep. It reaches the depth of several hundred metres. Sound Tegel has a greenish-grey colour, which changes to yellow-brown to reddish-brown colour and the zone of weathering closer to surface (Fig. 1). According to X-Ray analysis there is a substantial percentage of CaO (ca 20%) and the main minerals are kaolinite (ca 23%) and illite (22%), calcite (20%) quartz (17%), chlorite (up to 10%) and feldspar (Boháč et al., 1995). Tegel exhibits stiff to very stiff consistency. The clay is overconsolidated but the height of eroded overburden is not known. Above the Miocene clay there are Quartenary gravels overlain by loess loam (Fig. 2). The clay is tectonically faulted. The groundwater is mostly bound to Quartenary fluvial sediments, and the collectors are typically not continous. However the clay is fully water saturated.

In Tegel there is about 50% of clay fraction, w_L is about 75%, I_P about 43%, the soil plots just above the A-line at the plasticity chart and its index of colloid activity is about 0.9.

Figure 1. Exploratory adit of Dobrovského tunnels showing transition of weathered and sound Brno clay (Pavlík et al., 2004).

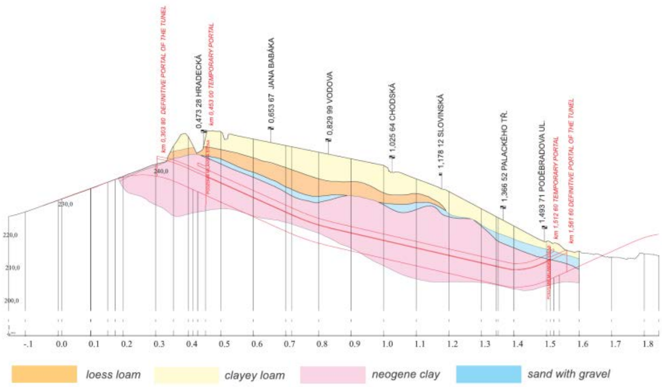

Figure 2. Longitudinal geological cross-section at the site of Dobrovského tunnels (Pavlík et al., 2004).

3 CIRCULAR EXPLORATORY ADIT

Circular adit R2 was excavated as a part of geotechnical site investigation for a major tunnelling project in the town of Brno, so called Dobrovského tunnels. The adit was located 26 m below the ground level, and its diameter was 1,9 m. Its plane view is shown in Fig. 3. The convergence profiles monitored are indicated by red lines in Fig. 3. The profile adopted in the present backanalyses is next to the label "SA216". The adit was protected by a steel net and steel arches TH (Touissant – Heitzmann). These were installed for safety reasons only, and the support was never in full contact with the cavity wall. Photography of the adit and safety support measures is in Fig. 4. As the support was not in full contact with the cavity wall, the monitored convergence is assumed to be representative of the displacement of an unsupported massif.

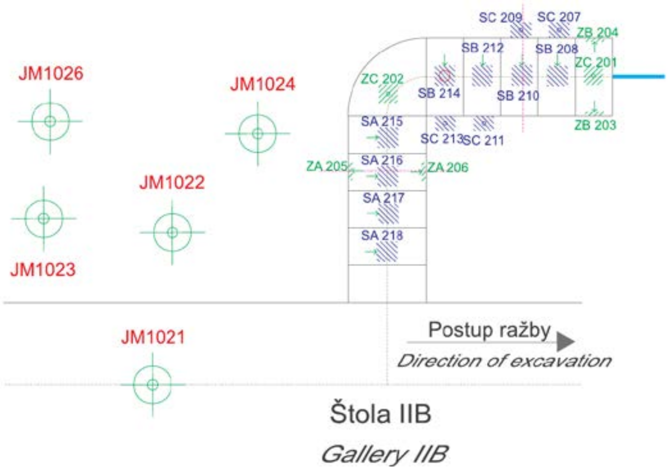

Figure 3. Geometry of the circular exploratory adit R2 excavated from the Gallery IIB (Pavlík et al., 2004).

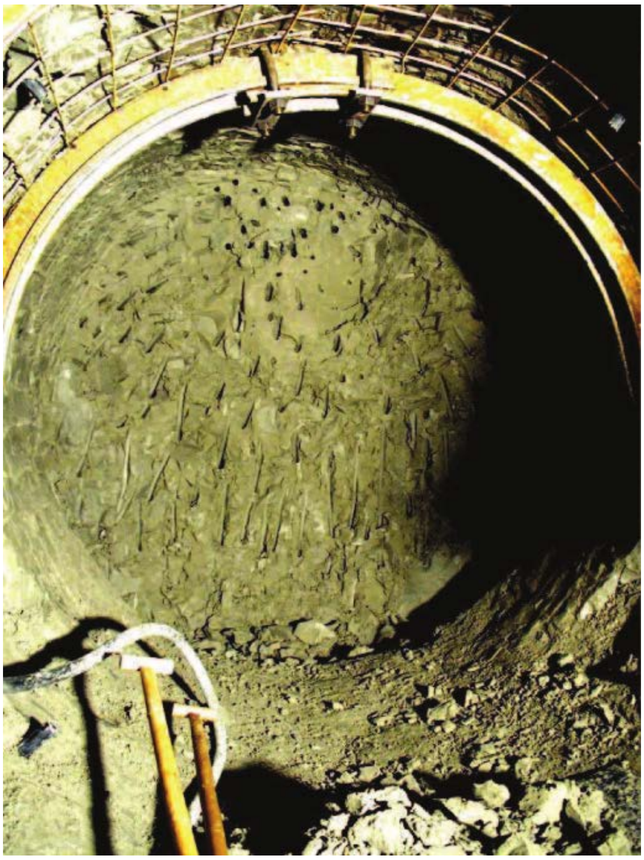

Figure 4. Safety support of the circular adit R2 (Pavlík et al., 2004).

The convergence of the circular cavity was monitored by means of push-rod dilatometer in four different directions (vertical, horizontal and two sections inclined at 45 degrees) by Pavlík et al. (2004). The obtained convergences and their dependence on time are clear from Fig. 5.

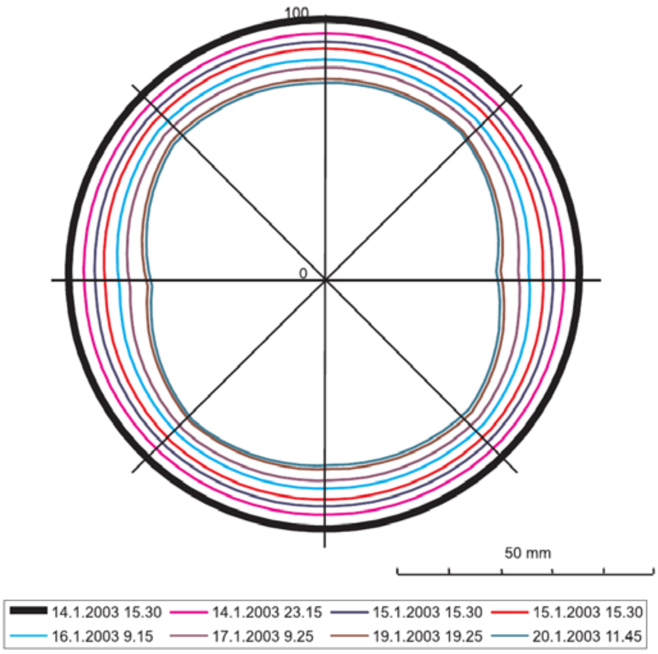

Figure 5. Results of the convergence measurement of the circular adit R2 (Pavlík et al., 2004).

4 NUMERICAL ANALYSES

The adit has been simulated in 2D and 3D using finite element method (software PLAXIS 2D and 3D). The geological sequence and material parameters were taken over from Svoboda et al. (2010), who simulated the main Dobrovského tunnels and triangular exploratory galleries.

The simulations are most significantly influenced by the constitutive model describing material behaviour of the Brno clay. In the simulations, hypoplastic model for clays by Mašín (2005) was adopted in combination with the intergranular strain concept by Niemunis and Herle (1997). This model is capable of predicting non-linear soil stiffness and its dependence on the strain level. It also predicts realistically the initial (very small strain) shear stiffness.

The constitutive model parameters were calibrated using quality laboratory experimental data. The experimental program adopted in the calibration involved:

- Oedometric testing of reconstituted specimens and undisturbed samples.
- Undrained triaxial (CIUP) testing of reconstituted specimens and undisturbed samples. Deformations were measured using displacement LVDT transducers attached directly onto the sample.
- Bender element testing of the very small strain shear stiffness by means of measurements the shear wave velocity propagation.
- Ring shear testing of reconstituted soil samples for estimation of the critical state friction angle.

Calibration of the parameters of the hypoplastic model has been described by Svoboda et al. (2010). In the presented simulations, slightly modified parameter set by Mašín (2012) has been used. The parameters of the hypoplastic model are summarised in Table. 1.

Table 2. Parameters of the hypoplastic model for clays used in the simulations.

φ_c	λ^*	κ^*	N	r
22°	0.128	0.015	1.51	0.45
m_R	m_T	R	β_r	χ
16,75	8.375	1.e-4	0.2	0.8

Other parameters involved in the simulations were as follows. The analyses were performed as undrained using penalty approach with bulk modulus of water equal to K_w = 10 GPa. The initial void ratio of the hypoplastic model was 0.83, the total unit weight of saturated soil was 18.8 kN/m^3 and position of water table coincided with the top of the Brno clay strata. All components of the the intergranular strain tensor, needed in the Niemunis and Herle (1997) model, were equal to 0. More information on selection of these parameters, as well as on properties of strata overlying Brno clay, can be found in Svoboda et al. (2010).

Procedure of the analyses was as follows. It was assumed that the massif properties were represented reasonably accurately. The initial value of K_0 was varied by a trial-and-error procedure until the model correctly reproduced the measured ratio of horizontal and vertical convergence of the adit. Measurements from 16. 1. 2003 (see Fig. 5), which means two days after beginning of the excavation, were adopted in the analyses. These measurements were selected for two reasons. First, they were measured soon after the onset of excavation and thus undrained conditions are realistic. Second, these measurements were taken before excavation of the perpendicular section of the adit (Fig. 3). The excavation of the perpendicular section could influence distribution of the displacements such that it could not be captured correctly using the plane strain 2D analyses. Other details of the analyses are summarised in the forthcoming sections.

4.1 *Numerical analyses in 2D*

Geometry adopted in the 2D analyses is depicted in Fig. 6. The 2D analyses were perfomed using the load reduction method (see Svoboda and Mašín, 2011). The analyses were perfomed in three phases.

1. In the first one, the initial conditions were calculated using the soil unit weight, precribed K_0 and water table position.
2. The second phase involved partial excavation of the adit until the load reduction factor λ_1 was reached. This simulation phase represented pre-convergence, i.e. massif displacements before the adit face reached the monitored section. Following recommendations by Svoboda and Mašín (2011), a fixed value of λ_1 = 0.5 was considered. During the second phase, water is present in the cluster corresponding to the future excavation.
3. The third phase represented displacements taking place after the adit face passed the monitored cross-section. The third phase was controlled by the factor λ_2. This factor is lower than unity, to represent the stabilising influence of the adit face which is located only few meters in advance of the monitoring section. In the third phase, the geometry cluster corresponding to the adit was considered as dry.

In the analyses, the load reduction factor λ_2 and the initial earth pressure at rest coefficient K_0 were varied iteratively by a trial and error procedure until the model represented correctly displacement magnitude (controlled by λ_2) and ratio of horizontal and vertical displacements (controlled by K_0).

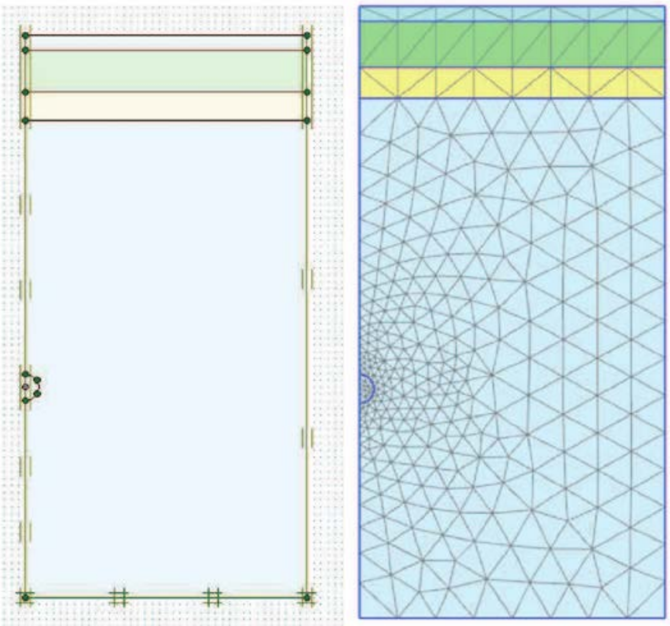

Figure 5. Geometry of 2D numerical model of the circular adit

4.2 *Numerical analyses in 3D*

The 3D modelling does not involve empirical load reduction factors in the simulations, and should thus in principle be more accurate than the 2D model. The geometry used in the analyses followed the actual geometry of the excavation. Figure 6 shows the adit detail and Figure 7 depicts the whole simulated domain.

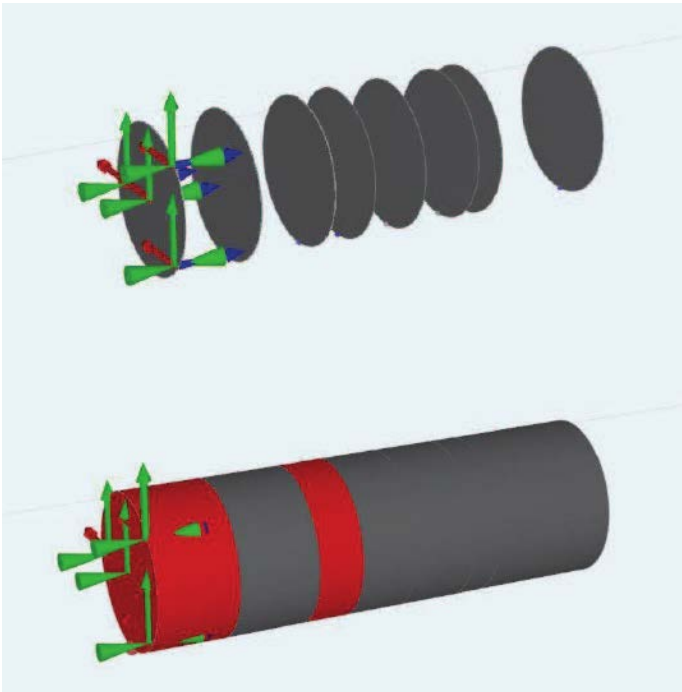

Figure 6. Detail of the geometry of 3D numerical model of the circular adit

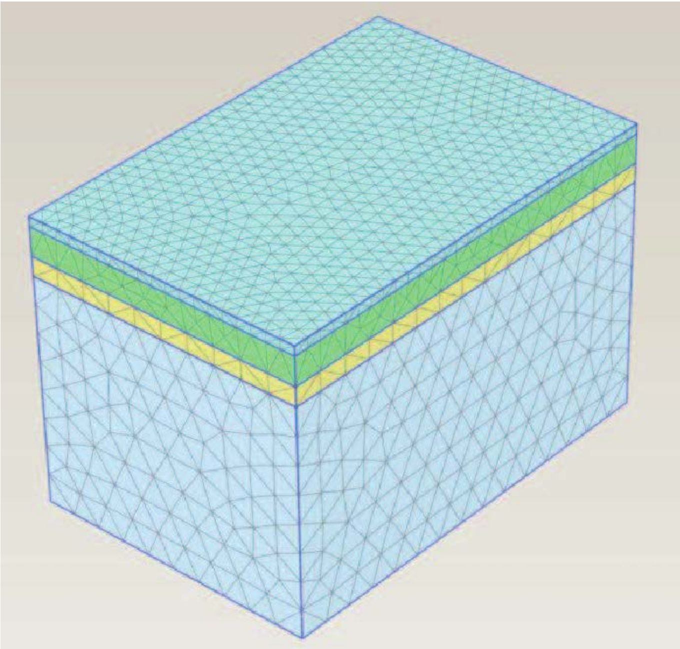

Figure 7. Simulated domain of the 3D numerical model of the circular adit

In the 3D model, only the first part of the excavation (without the perpendicular section) was analysed. The triangular gallery IIB (Fig. 3), from which the circular adit was excavated, was also not simulated explicitly in the analyses. It provided rigid support for the surrounding soil and its influence was represented by fixing the back of the adit in the longitudinal direction. To represent the real excavation and monitoring procedure, displacements were reset in simulations once the adit face passed the monitored section. They are thus not biased by the pre-convergence displacements, which are not registered by the rod dilatometers.
Obviously, the 3D analyses allow for less freedom in the model parameter variation, as there is no equivalent of the λ_2 factor. No effort was made to vary the model properties to reach the exact monitored displacement magnitude. K_0 was backanalysed only to fit the displacement ratio.

4.3 *Results of numerical analyses*

Example of evaluation of horizontal displacements in the monitored section in the 3D model is demonstrated in Fig. 8.

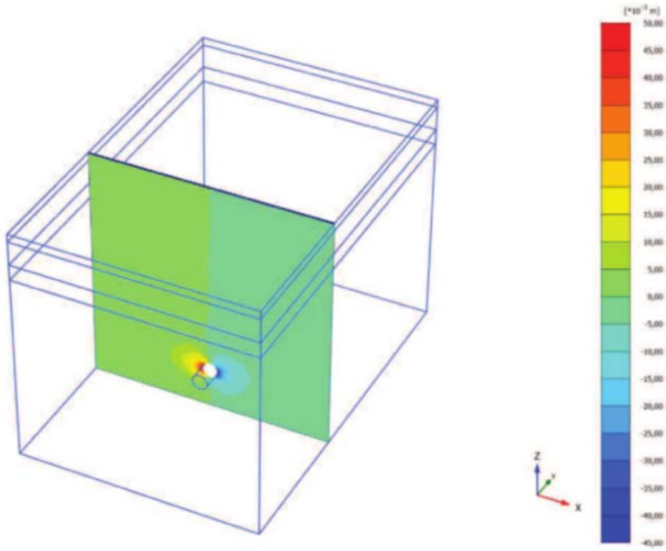

Figure 8. 3D model geometry and predictions of horizontal displacements.

Figure 9 shows the dependency of the ratio of horizontal and vertical displacements on the value of K_0 for 2D analyses. Increasing K_0 increases the ratio of u_h/u_v. as expected. Probably more surprising are results from Fig. 10, which shows the dependency of the magnitude of both horizontal and vertical displacements on K_0 (for constant value of the factor λ_2=0.67). Horizontal displacements are influenced only slightly by K_0, whereas vertical displacements decrease with K_0, relatively significantly, which leads to an increase of the ratio u_h/u_v.

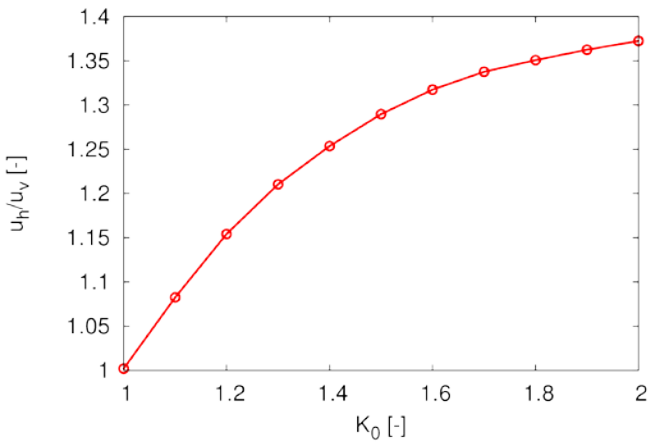

Figure 9. Dependency of the ratio of of u_h/u_v on the value of K_0 obtained in 2D analyses for constant value of the factor λ_2=0.67.

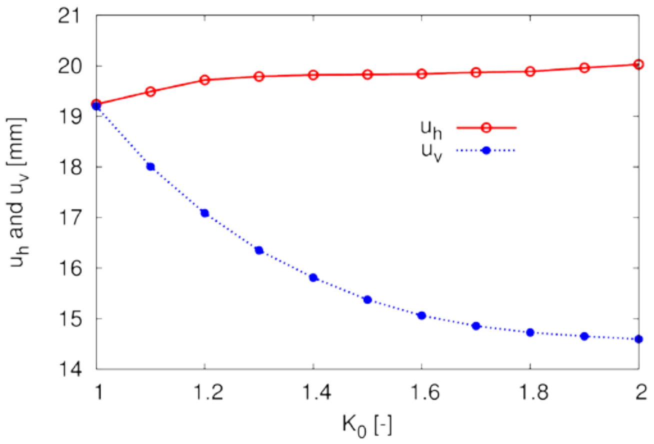

Figure 10. Dependency of the ratio of of u_h/u_v on the value of K_0 obtained in 2D analyses for constant value of the factor λ_2=0.67.

Final results of backanalyses in both 2D and 3D are summarized in Table 2. It is clear that the 2D and 3D analyses were relatively consistent in the estimation of K_0 (1.37 and 1.45 respectively). The 3D analyses overpredicted the displacement magnitude. Detailed discussion of the reasons for this overprediction is outside the scope of the present paper. However, the most likely reason is in that the hypoplastic model predicts linear dependency of the initial shear stiffness G_0 on mean stress level, whereas the dependency obtained by laboratory investigation is non-linear of the form G_0=5300 $p^{0.5}$. Hypoplasticity was calibrated to reproduce correctly the mean stress in the tunnel depth, and it thus undepredicts the stiffness during mean stress decrease, which occurs during the excavation. Stiffness underprediction then implies overprediction of displacements.

Table 2. Results of numerical backanalysis of circular exploratory adit.

	monitoring	2D model	3D model
horiz. conv. (u_h) [mm]	19.8	19.8	33.4
vert. conv. (u_v) [mm]	15.9	15.4	26.1
Ratio u_h /u_v	1.25	1.25	1.28
K_0	-	1.37	1.45

5 DISCUSSION OF HYPOPLASTIC MODEL LIMITATIONS

The most crucial factor influencing the ratio of horizontal and vertical convergence of the tunnel is the soil anisotropy. As discussed by Rott and Mašín (2012), it may be expected based on evaluation of experimental data on stiff clays by other investigators that the Brno clay is highly anisotropic in the very small strain stiffness, horizontal stiffness being about twice the vertical stiffness. Unfortunately, this stiffness anisotropy cannot be explicitly controlled in the adopted hypoplastic model. For this reason, the obtained values of K_0 need to be considered as preliminary. Anisotropic version of hypoplastic model is now being developed and once available will be used to precise the results presented in this paper.

6 CONCLUDING REMARKS

In the paper, we presented a numerical study aimed at investigating the earth pressure coefficient at rest K_0. A number of methods exist for K_0 determination, neither of them being flawless. In the present work, we adopted the approach based on backanalysis of convergence measurements of underground cavity of circular cross-section. The models were developer using finite element method in 2D and in 3D. Material behaviour was described using hypoplastic model. Both the models gave consistent results of K_0 equal approximately to 1.4. It is, however, emphasized that these values should be considered as preliminary, because the adopted model does not predict stiffness anisotropy.

ACKNOWLEDGEMENTS

The financial support by the grants P105/11/1884 and P105/12/1705 of the Czech Science Foundation, and by the grant MSM0021620855 is gratefully acknowledged.

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