Convergence-confinement method for simulating NATM tunnels evaluated by comparison with full 3D simulations

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The convergence-confinement method (CCM) for simulating NATM tunnels using plane strain finite element method was in the paper evaluated by comparison with fully 3D simulations. Three real shallow tunnels in urban environment in different stiff clays were simulated. The soil behaviour was described by an advanced non-linear soil constitutive model based on the hypoplasticity theory. It was shown that for an optimum value of the parameter λ_d the displacement field predicted by the CCM method agrees well with the 3D simulations. The controlling parameter was, however, found to be dependent on the problem simulated (for the same material) and also on the material properties (for the same tunneling problem).

1. INTRODUCTION

3D numerical analysis becomes an increasingly affordable tool for predicting deformations and stress redistribution induced by tunnelling. As tunnel excavation is clearly a three dimensional problem, considering the third dimension should intuitively lead to more accurate predictions. It might therefore be surprising that simplified procedures that allow us to consider 3D effects within a simplified 2D plane strain analysis are still popular in geotechnical design. This is because the 3D simulations require accurate description of such aspects as the excavation sequence, lining installation procedure, or time-dependent behavior of shotcrete, which may be difficult to incorporate in a numerical model accurately and they might not be feasible at preliminary design stages or for less demanding tunneling problems. 2D methods typically require specification of just a few or only one parameter (denoted in the following as λ_d), which integrates the influence of all of the aforementioned factors that need to be considered in 3D analyses. Calibrating λ_d based on monitoring results is popular as it is often possible to tune the model using a single empirical parameter such that some monitored aspect is correctly reproduced. Disadvantage of this approach is that it hinders eventual inaccuracies in description of the mechanical behaviour of the rock massif. This approach thus does not provide any information on the suitability of the 2D method itself to reproduce the 3D effects. The only way to proper evaluation of the 2D method thus lies in comparison of its predictions with predictions by equivalent fully 3D analyses.

2. STRESS-RELEASE (CONVERGENCE-CONFINEMENT) METHOD

At present, a number of 2D methods that can be used to account for 3D effects within finite element analysis framework is available. Probably the most popular method is the convergence-confinement method (CCM), introduced by Panet and Guénot (1982) with primary application to tunnel lining design. This method is nowadays commonly used to predict also displacement field due to NATM tunnelling. Panet and Guénot (1982) demonstrated that the 3D ground response to tunneling could be analysed with a plane strain approach, provided a fictitious pressure σ_r^f was introduced inside the tunnel area in the 2D model. This pressure could be derived from the initial stress in the ground σ_r^O from

$$\sigma_r^f = (1-\lambda)\sigma_r^0 \quad (1)$$

where λ is the stress release coefficient. Its value corresponding to the moment of lining instalation is denoted as λ_d . The method can be properly evaluated by means of comparison of 2D with fully 3D simulations. Such comparison, however, are scarce in the technical literature. The aim of this paper is to investigace:

- whether λ_d depends on the problem geometry, i.e. whether the same λ_d can be used for predictions of different tunnels in the same material.
- to what extent λ_d depends on material properties, i.e. whether the same λ_d can be used for predictions of a tunnel advancing through different geological materials.

3. 3D SIMULATIONS OF CASE STUDIES ANALYSED

3D finite element models of three case histories will be used as a basis for the evaluation of the CCM method. All of the cases represent shallow NATM tunnels excavated in stiff clays in urban environment. Results of the 3D analyses were thoroughly checked with respect to monitoring data to demonstrate realistic representation of the three dimensional effects. Soil properties were described by means of an advanced nonlinear constitutive model for fine-grained soils, a hypoplastic constitutive model for clays (Mašín 2005) enhanced by the intergranular strain concept (Niemunis and Herle 1997). This model has been shown to represent accurately the soil behaviour from the very small strain range to large strain range, including high quasi-elastic stiffness in the very small strain range and its non-linear decrease with increasing strain level. Finite element simulations were performed using software Tochnog Professional (Rodemann 2008). In all cases, undrained analyses were performed with reduced value of water bulk modulus K_w to account for consolidation effects. Realistic excavation sequence as applied in the field was simulated. Lining behaviour was described by a linear elastic model with time-dependent Young modulus following an exponential expression by Pottler (1990). Continuum elements, rather than shell elements, were used to simulate tunnel lining. For a detailed description of the analysis procedures see Mašín (2009).

3.1. Heathrow express trial tunnel

Heathrow express trial tunnel (Deane and Basset 1995), a NATM tunnel built in London Clay to test effectiveness of the shotcrete lining method, has since become a classical example for evaluation of different numerical tools. In this work, 3D analyses described in detail by Mašín (2009) will be used as a basis for evaluation of the CCM method. Hypoplastic constitutive model was calibrated using high quality experimental data on London Clay by Gasparre (2005). All the simulations were performed with a constitute model calibrated solely on the basis of laboratory experiments, without tuning material parameters to obtain monitored deformations. High K_0 values varying with depth, as measured in situ by Hight et al. (2007), were considered. Finite element mesh and the modelled geometry is shown in Figure 1.

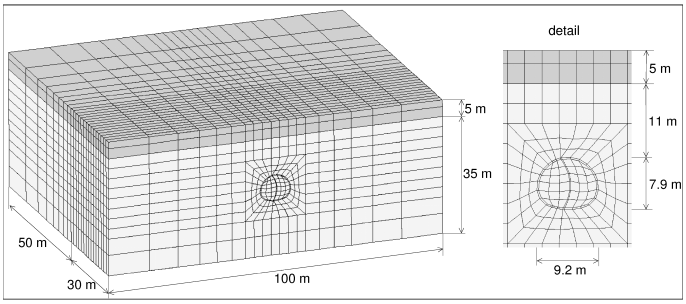
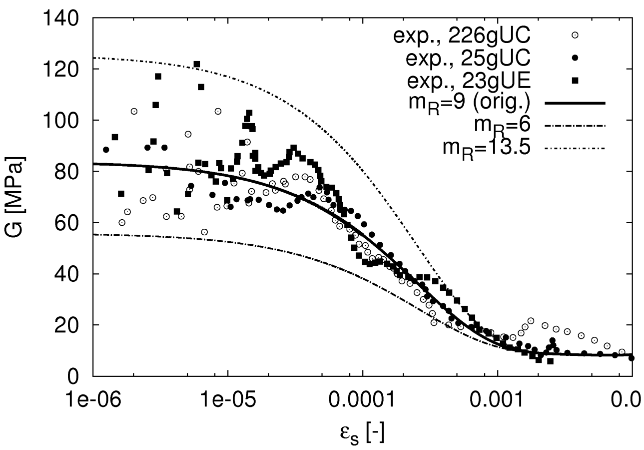


Figure 1: Finite element mesh used in the analyses of the Heathrow express trial tunnel (from Mašín, 2009).



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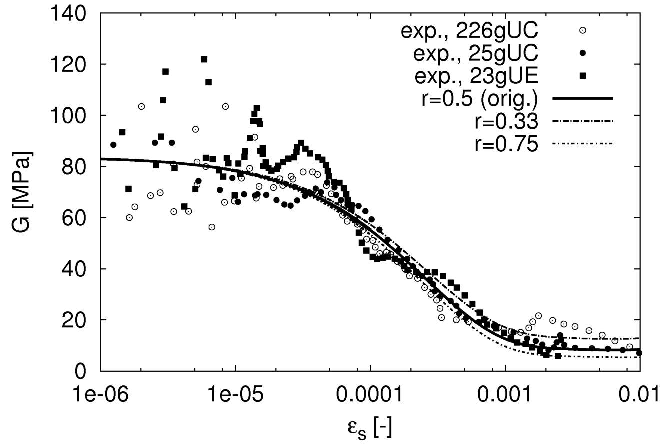
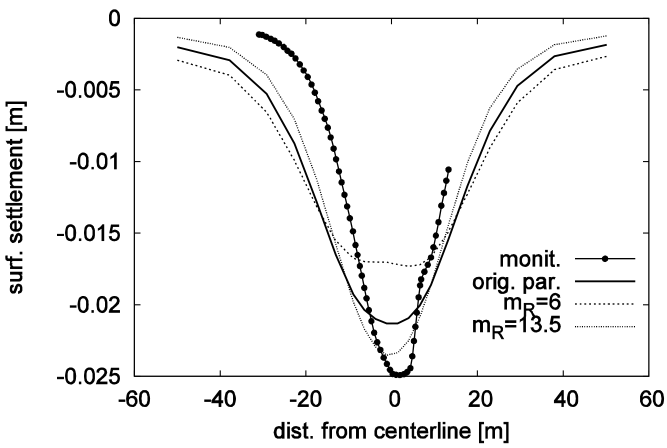


(b)

Figure 2: Stiffness degradation curves simulated by the hypoplastic model with different parameters (from Mašín, 2009). Experimental data on natural samples of London Clay from Gasparre (2005).

Mašín (2009) performed a parametric study aimed at clarification of the influence of material parameters on the predicted results. Figure 2 shows shear stiffness degradation curves for undrained shear triaxial tests on natural samples of London Clay simulated using the hypoplastic model with different values of material parameters. As is clear from Figure 2, the parameter m_R controls the initial stiffness in the very small strain range, while the parameter r controls the large strain stiffness (constant initial stiffness was imposed in the analyses while varying parameter r). Values $m_R = 9$ and $r = 0.5$ represent the best the experimental data. Surface settlement troughs predicted by the 3D model are shown in Figure 3. With parameters calibrated solely on the basis of laboratory experiments, the model is capable of reproducing the settlement magnitude, while it slightly overestimates the settlement trough width. Although the influence of the large strain stiffness (parameter r) appears to be insignificant in Fig. 2b, it has a substantial effect on the predicted settlement magnitude (Fig. 3b).



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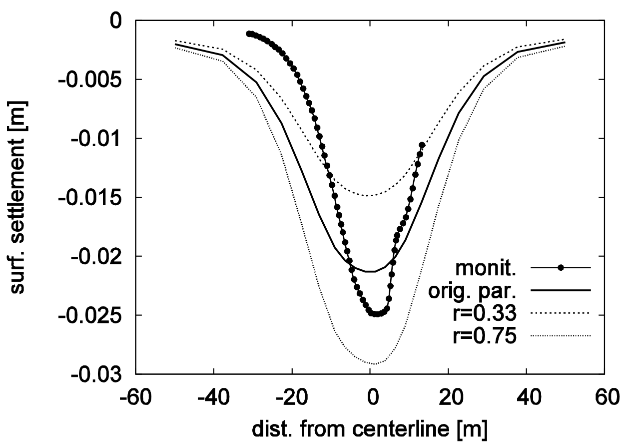


(b)

Figure 3: The influence of the small-strain stiffness characteristics on the predicted settlement trough for the Heathrow express trial tunnel (from Mašín, 2009; monitoring data from Deane and Basset 1995).

3.2. Dobrovskeho exploratory adit

The second case study analysed is an exploratory adit of the Dobrovskeho tunnel, which is being excavated in Brno, Czech Republic. These tunnels form the northern part of the large city ring road. The tunnels consist of two oval tunnel tubes with lengths 1.2 km with height of about 12 m, a section width of about 14 m. 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. For exploration purposes, three adits were excavated. The exploratory adits had approximately triangular cross sections with side length 5 m and were situated in the tunnel top headings. The subsoil in which the tunnels are excavated consists of Miocene limy, silty stiff clay (Brno Clay). Full 3D numerical model of the exploratory adit has been developed by Svoboda and Mašín (2009). The parameters of the hypoplastic model for clays were calibrated on the basis of quality laboratory experiments that included measurements of small strain stiffness characteristics using local LVDT strain transducers and bender elements. FE mesh and the model geometry are shown in Figure 4.

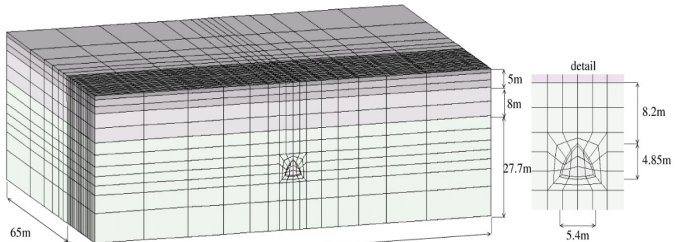
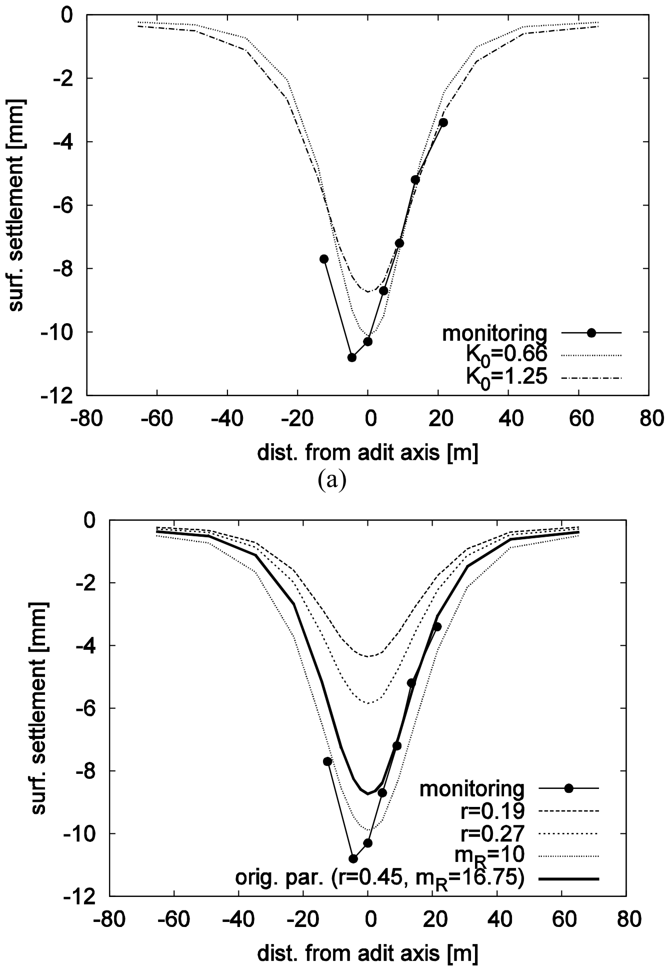


Figure 4: Finite element mesh used in the analyses of the exploratory adit of Dobrovskeho tunnel (from Svoboda and Mašín, 2009)

As no measurements of the coefficient of earth pressure at rest K_0 have been performed on the site, simulations were performed with two different extreme values of K_0. One considers the apparent overconsolidation of the soil deposit caused by mechanical unloading. K_0 is then calculated using an approach proposed by Mayne and Kulhawy (1982) leading to $K_0 = 1.25$. The second assumes that overconsolidation is caused by creep phenomena with $K_0 = 0.66$ obtained from Jáky (1944) formula. Surface settlement troughs predicted by the hypoplastic model for the two K_0 values are shown in Fig. 5a.



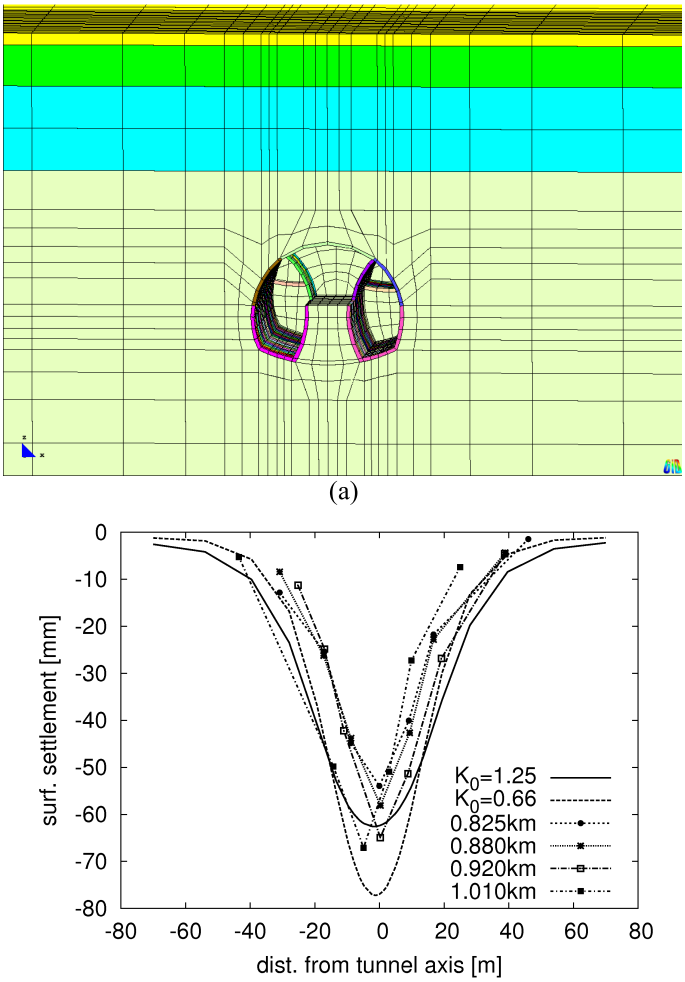
(b)

Figure 5: Surface settlement trough due to exploratory adit of Dobrovskeho tunnel predicted by the 3D analysis for two different K_0 values (a) and for different model parameters with $K_0 = 1.25$ (b).

Analysis with $K_0 = 0.66$ represents the monitored behaviour better, but in general the K_0 value does not have a substantial effect on the settlement trough. Again, realistic predictions were obtained with the constitutive model calibrated solely on the basis of laboratory experimental data. Additional analyses were performed with variable parameters *r* (large strain stiffness) and m_R (small strain stiffness) for $K_0 = 1.25$. The influence of these characteristics on the small strain stiffness is similar to the one from Figure 2. Figure 5b shows that both small and large strain stiffness influence the settlement trough predictions.

3.3. Dobrovskeho tunnel

In addition to the simulations of the exploratory adit of Dobrovskeho tunnel, full 3D model of the whole tunnel has been created. The model considered rather complex excavation sequence followed at the site, with the tunnel face subdivided into 6 segments. Two cases were considered. One with original model parameters calibrated on the basis of laboratory experiments, the second with parameters optimised based on monitoring results from exploratory adit (see Svoboda and Mašín 2008 and Svoboda and Mašín 2009 for details). Only simulations with the original parameter set are considered in this paper, so that direct comparison with simulations of the exploratory adit is possible. Simulations represent „class A“ predictions of deformations due to the tunnel, as the tunnel has not been built by the time the authors were performing the simulations. Geometry of the 3D model during simulation of the complex excavation sequence is in Fig. 6a, predicted surface settlement troughs compared with the monitoring data for the two K_0 states in Fig. 6b.



(a)

(b)

Figure 6: 3D model of the Dobrovskeho tunnel (a) and surface settlement troughs predicted for two different K0 values (b) compared with monitoring data (tunnel chainage).

4. 2D ANALYSES BY THE CONVERGENCE-CONFINEMENT METHOD

To study the applicability of the CCM method, 2D equivalents of all the 3D models presented have been prepared. Basic version of the CCM was adopted, i.e. time dependency of the lining stiffness, which has been considered in the 3D analyses, was not modelled. In 2D, truss-beam elements were used to represent the lining, whereas in 3D, lining was modelled using continuum elements. The CCM controlling parameter λ_d was calibrated to ensure that the 2D and 3D analyses predicted as closely as possible the surface settlement troughs (the overall displacement fields were studied subsequently). In order to prevent subjectivity of the λ_d determination, it was calibrated using a software tool specifically devised for optimisation analyses and inverse modelling UCODE (Poeter and Hill 1998). For other applications of this software in geotechnical engineering optimisation problems see Finno and Calvello (2005). The following procedure was applied. The vertical surface displacements computed by the CCM method in different distances from the tunnel axis (approx. 20 locations) were used to assemble a „simulation vector“ y', whereas displacements obtained by the 3D analyses formed an „observation vector“ y. The difference was quantified by means of a weighted least-squares objective function *S(b)* expressed as

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

where b is a vector containing values of parameters to be estimated (in our case a single parameter λ_d) and w is a weight matrix, considered as a unity matrix for simplicity. Minimisation of the objective function *S(b)* was accomplished by UCODE with the modified Gauss-Newton method.

5. SUMMARY OF THE CCM ANALYSES AND DISCUSSION OF RESULTS

Altogether 12 simulations have been performed and evaluated. They correspond to the 3D simulations described in Sec. 3. Results are summarised in Tab. 1, which gives values of the CCM parameter λ_d corresponding to the minimum value of the objective function *S(b)*. In addition, relation between very small strain and large strain shear moduli used in simulations (G_0*(simul.)* and G_{ls} *(simul.)* respectively) and their original values calibrated using laboratory experiments (G_0 and G_{ls} respectively) is indicated. The table also indicates the initial K_0 conditions.

5.1. Dependency of λ_d on different studied factors

The following observations may be summarised based on results presented in Tab. 1. λ_d depends on the assumed material parameters, i.e. on the soil type. The very small strain shear modulus G_0 influences λ_d remarkably. Interestingly, λ_d does not appear to be influenced significantly by the soil behaviour in the large strain rage. Varying the very small strain shear modulus G_0 imposed changes of λ_d of the order of 0.1 in comparison with the original values, while varying G_{ls} had only slight effect on λ_d of the order of 0.03 at maximum. This result might appear surprising, as both G_0 and G_{ls} were shown to have substantial effect on the predicted displacements, both for the Heathrow express trial tunnel (Fig. 3) and Dobrovskeho exploratory adit (Fig. 5).

Table 1: Summary of the CCM simulations

Case study	$G_0(simul.)$	$G_{ls}(simul.)$	K_0	λ^d
Heathrow	$= G_0$	$= G_{ls}$	variable	0.56
Heathrow	$= G_0$	$> G_{ls}$	variable	0.59
Heathrow	$= G_0$	$< G_{ls}$	variable	0.53
Heathrow	$< G_0$	$= G_{ls}$	variable	0.48
Heathrow	$> G_0$	$= G_{ls}$	variable	0.65
Dobr. - adit	$= G_0$	$= G_{ls}$	1.25	0.50
Dobr. - adit	$= G_0$	$\gg G_{ls}$	1.25	0.52
Dobr. - adit	$= G_0$	$> G_{ls}$	1.25	0.53
Dobr. - adit	$< G_0$	$= G_{ls}$	1.25	0.40
Dobr. - adit	$= G_0$	$= G_{ls}$	0.66	0.53
Dobr. - tunnel	$= G_0$	$= G_{ls}$	1.25	0.32
Dobr. - tunnel	$= G_0$	$= G_{ls}$	0.66	0.35

One of the consequences of this observation is that a change of geological conditions during excavation of a single tunnel might require appropriate modification of λ_d values used in the simulations. K_0 does not appear to have substantial effect on λ_d. For the same soil type, the tunnel size and geometry influences significantly appropriate values of λ_d . In the case of the Dobrovskeho study, $\lambda_d \approx 0.5$ was found for the exploratory adit, whereas $\lambda_d \approx 0.3$ for the whole tunnel. Thus, if λ_d found on the basis of results of an exploratory adit simulations was used for predictions of the full tunnel response, it would lead to an overestimation of the tunnel deformations. This is demonstrated in Fig. 7, in which the Dobrovskeho tunnel simulations are repeated with λ_d calibrated based on simulations of exploratory adit. These simulations lead to approximately 35% larger surface settlements.

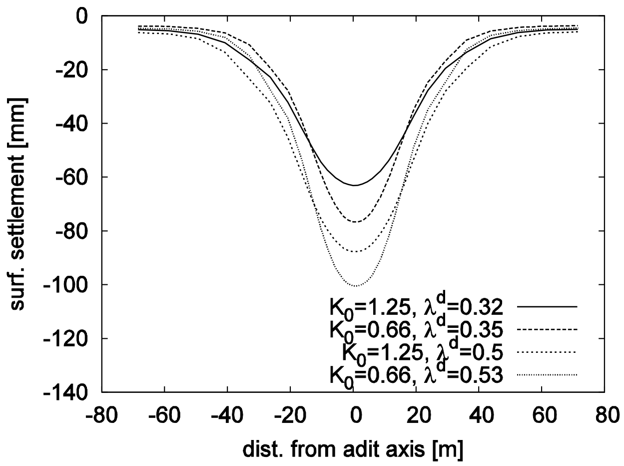
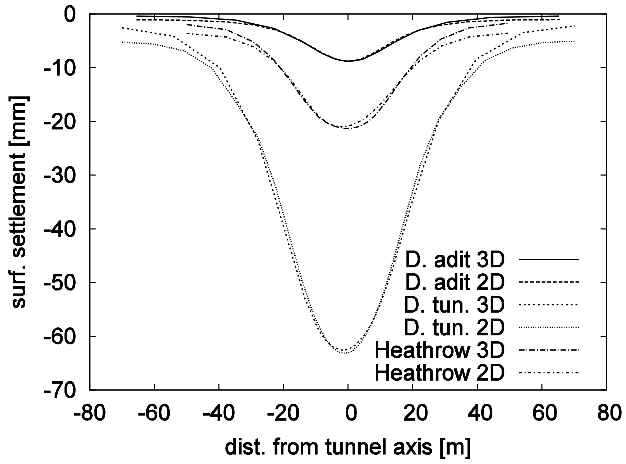


Figure 7: The influence of λ_d on the CCM predictions of Dobrovskeho tunnel.

5.2. Accuracy of the CCM predictions

Accuracy of the CCM predictions was studied on the basis of analyses of the three case histories with the original parameter values (and $K_0 = 1.25$ for Dobrovskeho case studies). Figure 8 shows predictions by the CCM method and full 3D method for the three case studies analysed. Figure 8a gives surface settlement troughs, Fig. 8b shows horizontal displacements from an inclinometer located approximately 1D from the tunnel boundary, and Fig. 8c gives vertical displacements from an extensometer located above the tunnel axis. The surface settlement troughs by the 2D and 3D methods match very well. An overall agreement could have been expected, as λ_d was calibrated with the intention to match the surface settlement trough as accurately as possible, but it is interesting to observe that also the settlement trough shape is predicted accurately by the 2D method. Plots of variation of vertical and horizontal displacements with depth show good agreement for the Heathrow express case. For both Dobrovskeho adit and Dobrovskeho tunnel, the 2D method underestimates the displacements within a distance of approximately 1 tunnel diameter from a tunnel. The predictions match well outside this region. The overall field of vertical displacements is shown in Fig. 9. An overall agreement of 2D and 3D method is good. The most notable discrepancy is in the predictions of the exploratory adit. The 2D method predicts higher vertical displacements above the sides of the adit then above its axis. This is caused by high K_0 conditions adopted in the Dobrovskeho case study analyses presented in this section ($K_0 = 1.25$). In the 3D analyses, this effect is not that significant and the method predicts more reasonable shape of the vertical displacement field in a close vicinity of the adit.



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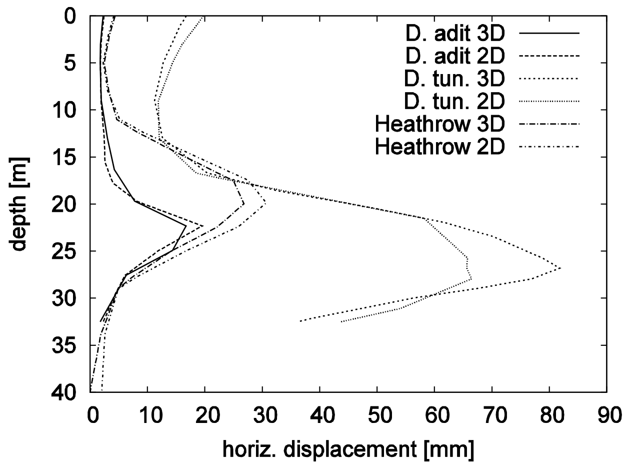

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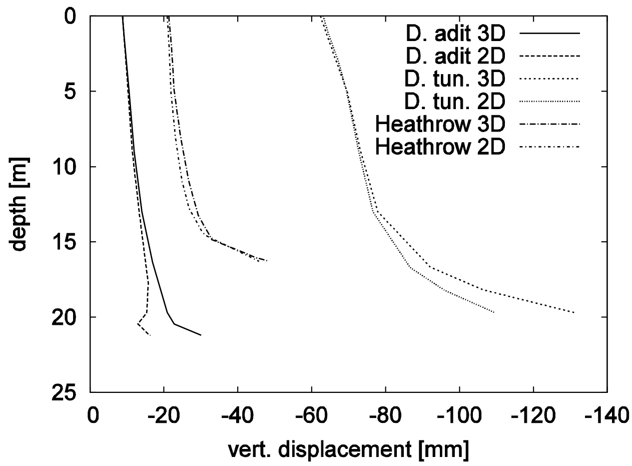

(c)

Figure 8: Comparison of surface settlement troughs (a), inclinometer results (b) and extensometr results (c) predicted by the 3D and 2D methods for the three case studies analysed.

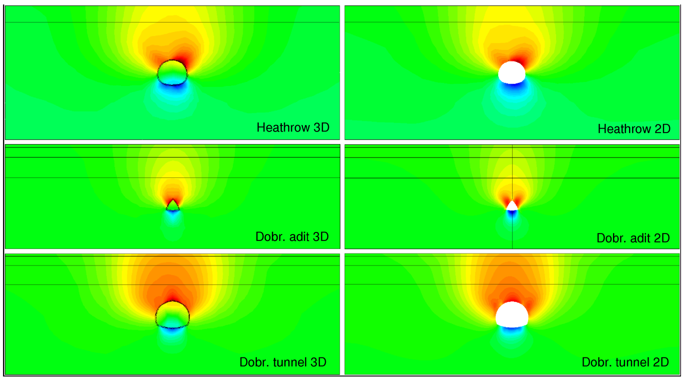

Figure 9: Qualitative comparison of vertical displacement field predicted by the 3D and 2D methods for the three case studies analysed (the same color scale for corresponding 2D and 3D analyses).

6. CONCLUDING REMARKS

The 2D convergence-confinement method for simulating NATM tunnels using plane strain finite element method was in the paper evaluated by comparison with fully 3D simulations of three different case histories. It was shown that for an optimum value of the CCM parameter λ_d the displacement field predicted by the CCM method agrees well with the 3D simulations. In some cases only, a discrepancy was observed in a close vicinity of the tunnel. The parameter λ_d was found to be dependent on the problem simulated (for the same material) and also on the material properties (for the same tunneling problem). Considering material properties, the very small strain shear modulus was found to be more influential on the λ_d value than the large strain shear modulus. The initial K_0 stress state was not found to influence λ_d substantially.

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