Tunnel face stability as a function of the purchase length

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Abstract

In geomechanical engineering the stability of the tunnel face appears to be one of the most decisive items in the list of assessments needed for verification of bearing capacity of the system tunnel – surrounding rock. Studies following from on site measurements are very expensive and depend strictly on the nature of material being involved in the study. Experiments conducted on scale models in stands which are filled by physically equivalent materials are more promising and complex, as instrumentation of smaller samples is richer and more flexible than in the case of treatment on real site. Moreover, numerical modeling, which requires a particular description of material behavior of the structures coming into the computational models, can be derived from physical models in an easier way than from real tunnel behavior. A numerical approach is proposed in such a way that internal parameters of a mathematical physically nonlinear model are evaluated using partial results of experimental scale models from equivalent materials. Although basically strongly nonlinear problems are solved, solution of linear algebraic equations is the final step of the approach for identification of values of internal parameters characterizing material properties in mathematical simulation of reality. Tunnel face stability in dependence of a length of work-out space is solved in this paper using coupled modeling, as an example of application of the procedure envisaged.
Keywords: fiber reinforced concrete lining, tunnels, coupled modeling, eigenparameters, effect of tunnel lining stiffness.

WIT Transactions on the Built Environment, Vol 102,
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/US080091

1 Introduction

In assessment of underground structures a combination of experiments and mathematical treatments are of great interest for designers and researches. Such a coupling enables one to improve information needed in numerical modeling on mechanical behavior of structural elements being employed in the problem at relatively low cost. The following approaches can be distinguished in practice:
- Convergence analysis, comparing results from experiments and pilot numerical analysis and successively adjusting material parameters in such a way that the numerical results are in reasonable agreement with the experimental.
- Back analysis, or coupled modeling is defined as a process, in which a qualitative and quantitative measure of agreement with experimental results is ensured in mathematical model and suggests approaches, by virtue of which internal parameters of different kind are adjusted to be in compliance with experiments as close as possible. In most cases fitting of physical laws (generalized Hooke's law, creep, relaxation, aging, etc.) is sought, but sometimes new geometry arrangement is required.

Previously Cividini, et al., [1] suggested a successful approach leading to a comparative study of the rock and tunnel lining behavior and the reality in terms of internal parameters (material properties). The paper presents a discussion on some of the aspects of parameter "characterization" problems (or back analyses) in the field of geomechanics.

In 1992 Dvorak established Transformation Field Analysis, [2], which expressed nonlinear problems in a hull of linear effects and effects of eigenparameters. This method appeared a powerful tool for solving optimal prestress of a thick-walled composite cylinder consisting of many different cylindrically orthotropic layers being loaded by uniform, axisymmetric tractions and by piecewise uniform eigenstrains in the layers, [3]. The first attempts have been done in [4] to involve the eigenparameters in the coupled modeling. The starting point for this approach was elastic state and effect of eigenparameters was expressed by combination of products of influence matrices and eigenparameters. In this paper sophisticated experimental approach leading to an observation of effect of work-out space to displacements of the tunnel face is presented. The displacements can then be used in the coupled modeling.

2 Numerical modeling

As said in Introduction, the idea of the back analysis used here starts with similar assumptions and approaches as in Transformation Field Analysis (TFA). This idea is basically very simple. Consider a generalized Hooke's law, i.e. let us relate overall stresses $\boldsymbol{\sigma}$ with overall strains $\boldsymbol{\varepsilon}$ and eigenstrains $\boldsymbol{\mu}$, or eigenstresses $\boldsymbol{\lambda}$, which may be realized as generalization of the influence of temperature: $\boldsymbol{\sigma} = \boldsymbol{L}(\boldsymbol{\varepsilon} - \boldsymbol{\mu}) = \boldsymbol{L}\boldsymbol{\varepsilon} + \boldsymbol{\lambda}$, where $\boldsymbol{L}$ is the purely elastic material stiffness matrix. This generalization differs from description of the temperature in such a way that the temperature appears in Hooke's law as the trace in the strain tensor while eigenstrains or eigenstresses are full-value tensors of the second order.

In order to formulate the general procedure for the TFA, it may be done in terms of many modern numerical methods. First, let us consider that the body (part of a structure, element, and system of more elements, composite, rock, soil) behaves linearly, i.e. Hooke's linear law is valid in the entire body. When the problem is correctly posed, the displacement vector, strain and stress tensors can be obtained from the Navier equations, kinematical equations, and linear Hooke's law.

In the second step we select points, where the measured values are available, either from experiments in laboratory, or from "in situ" measurements. We also select points, or regions (subdomains) from the body under study, and apply there successively unit eigenparameter impulses (either eigenstresses or eigenstrains) to get an influence tensors (matrices). In order to precise this statement, denote A_i, $i = 1,...,n$, either the points or regions where the eigenparameters will be applied. Let, moreover, the set of points where the measured values are known, be B_j, $j = 1,...,m$. Then the real stress at B_j is a linear hull of stress $\boldsymbol{\sigma}^{\text{ext}}$ at B_j due to external loading and eigenstrains $\boldsymbol{\mu}$ (or eigenstresses $\boldsymbol{\lambda}$) at A_i (similar relations are valid for overall strain field ε) leads us to relations as

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^{\text{ext}} + \boldsymbol{P}^{\sigma}\,\boldsymbol{\mu}, \quad \text{or} \quad \boldsymbol{\sigma} = \boldsymbol{\sigma}^{\text{ext}} + \boldsymbol{R}^{\sigma}\,\boldsymbol{\lambda}\ , \tag{1}$$

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{\text{ext}} + \boldsymbol{P}^{\varepsilon}\,\boldsymbol{\mu}\ , \quad \text{or} \quad \boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{\text{ext}} + \boldsymbol{R}^{\varepsilon}\,\boldsymbol{\lambda}\ , \tag{2}$$

where the influence tensors, $\boldsymbol{P}$ and $\boldsymbol{R}$**,** are obtained from the unit impulses of eigenparameters introduced on selected regions A_i , $i = 1,...,n$. Note that in 3D the eigenparameter tensor is symmetric, so that six components are available as the design parameters in one region. The components of influence matrices are created from responses of stresses or strains in elastic medium again. The dimensions of $\boldsymbol{\sigma}$, $\boldsymbol{\sigma}^{\text{ext}}$, $\boldsymbol{\mu}$, and $\boldsymbol{\lambda}$ are $m \times 6$ (because of symmetric stress and strain tensors) and the dimensions of $\mathbf{P}$ and $\mathbf{R}$ are $m \times 6 \times n$.

Note that it holds: $\boldsymbol{\lambda} = -\boldsymbol{L}\,\boldsymbol{\mu}$. The free, or design parameters, which should be selected in such a way that the measured and calculated values are mutually as close as possible, can be determined from many approached. One of them is suggested in the next text, starts with formulation of an optimization problem, and can be considered a back analysis procedure.

Without any details we can assert that similar relations as that of (1) and (2) can be written for displacements:

$$(u_i)^k = (u^{\text{ext}}{}_i)^k + \sum_{j=1}^{6} \sum_{l=1}^{m} (R^{\text{u}}{}_{ij})^{kl}(\lambda_j)^l, \quad i = 1,...,6,\ \ k = 1,...,m \tag{3}$$

On the other hand measured stresses $(\sigma_i^{\text{meas}})^k$, or measured displacements $(u^{\text{meas}}{}_i)^k$ are available in a discrete set of points (namely the points B_i). A natural requirement is that the values of measured and computed values be as close as possible. This leads us to the optimization of an "error functional"

$$I[(\lambda_j)^l] = \sum_{i=1}^{6} \sum_{k=1}^{m} [(\sigma_i)^k - (\sigma_i^{\text{meas}})^k]^2 \quad \rightarrow \ \text{minimum}\ , \tag{4}$$

or

$$I[(\lambda_j)^l]=\sum_{i=1}^{6}\sum_{k=1}^{m}[(u_i)^k-(u_i^{\mathrm{meas}})^k]^2 \rightarrow \text{minimum} \tag{5}$$

Differentiating I by $(\lambda_\alpha)^\beta$ yields

$$\sum_{l=1}^{n}(A_{\alpha j})^{\beta l}(\lambda_j)^l=Y_\alpha^\beta,\ \ \alpha=1,...,6,\ \beta=1,...,\mathrm{m}, \tag{6}$$

where

$$(A_{\alpha j})^{\beta l}=\sum_{i=1}^{6}\sum_{k=1}^{m}(R_{ij})^{kl}(R_{i\alpha})^{k\beta},$$

$$Y_\alpha^\beta=-\sum_{i=1}^{6}\sum_{k=1}^{m}(\sigma_i)^k-(u^{\mathrm{meas}}{}_i)^k+\sum_{j=1}^{6}\sum_{l=1}^{m}(R_{ij})^{kl}(\lambda_j)^l(R_{i\alpha})^{k\beta}$$

3 Physical modeling

Physical modeling is important for study of effects taking place in rock material in connection with construction of underground structures. The modeling allows us to investigate mechanisms of geotechnical phenomena, predicts stress changes and their demonstration during various progresses of underground construction and also during simulation of operating conditions.

Basic rules of the experimental modeling and formulation of the boundary conditions for modeling comes out from the principles of geometrical and physical similarity which is inferred for a consideration of dimensional analysis, [5]. Such a similarity modeling applied to slope stability is published in [6], for example. To simplify the solved problem constitutive relevant quantities v_1, $v_2,...,v_n$ can be selected, which posses exercise decisive influence to process taking place in the rock material. We assume that influence of the other quantities is lesser. Then physical equation involving function of relevant quantities of various dimensions

$$F(v_1, v_2, \ldots, v_n)=0, \tag{7}$$

describes in simplification, given by selection of these quantities, behaviour of the rock material. According to the Buckingham theorem this dimensional equation for relation between reality and model can be reduced to the problem of finding $k < n$ relevant non-dimensional parameters π_i. They are functions of v_i, fulfil the above equation (7) and are numerically identical for model and reality. By implementation of non-dimensional parameters π_i, for which from requirement of dimensional homogeneity follow

$$\pi_i=v_1^{x_{1i}}\ v_2^{x_{2i}}\ \ldots\ v_n^{x_{ni}},\ (i=1,2,\ldots,k)$$

non-dimensional physical equation is obtained

$$F'(\pi_1,\ \pi_2,\ldots,\ \pi_k)=0,$$

in which arguments π are dimension independent. Non-dimensional parameters π_i correspond to basic central processing units $\boldsymbol{L}$ (length), $\boldsymbol{T}$ (time), $\boldsymbol{M}$ (mass).

Physical model has to obey geometrical similarity; in reality it is a proportionality of dimensions and angles between model and modeled object in the whole range of the model.

In the modeled geotechnical problems the ratio of length dimensions of the model and reality plays very important role (and is given from the intended geometry of the scale model). If $1/\alpha_l$ is the length scale, i.e. ratio of lengths in the model and reality and a is the ratio of bulk densities

$$a = \rho_{\mathrm{model}}/\rho_{\mathrm{reality}},$$

then we can define ratios for the following quantities

forces $P_{\mathrm{model}} = a.\,(1/\alpha_l)^3\,.\,P_{\mathrm{reality}}$

stresses $\sigma_{\mathrm{model}} = a.\,(1/\alpha_l)\,.\,\sigma_{\mathrm{reality}}$

deformations $\varepsilon_{\mathrm{model}} = a.\,(1/\alpha_l)\,.\,\varepsilon_{\mathrm{reality}}.$

Time as such asserts oneself during derivation of non-dimensional parameters determined from a system of equations in relevant variables and corresponding basic units. To determine time scale ratio of the time in reality and in the model empirical estimation is applied (in terms of time needed for stress redistribution in the model body caused by pressure changes in model in comparison to time when the same process took place in reality). This time scale is applied for assessment of the rest quantities depending on time. Generally time scale can be determined as

$$\alpha_t = (v_{\mathrm{model}}/v_{\mathrm{reality}}).\,\alpha_l,$$

where

α_t – time scale

α_l – length scale

v – velocity of deformation.

To simulate the most perfect processes taking place in the rock material, rock environment is replaced in the model by equivalent materials their determinate physical and mechanical properties according model laws and scale of model agree with rock properties and respect the character of failures simulating those in rock material. The models are constructed from mixture of various, mostly easy available materials (e.g. sand, bentonite, ballotine, gypsum, mica - vermiculite, composite mortar, cellular concrete and water).

The models are constructed in stands of various dimensions in dependence of solving problem and length scale of the model.

4 Example

The experiments are focused on physical models on a scale 1 : 100, in a model stand. In the models rock material is substituted by physically equivalent materials, which consist of various mixtures of sand, bentonite and fat (65% + 29% + 6%), and moisture. Their properties are determined by standard tests:

volume mass ρ	1.45 g/cm^3
compressive strength σ_t	0.027 MPa
strength in simple tension σ_c	0.006 MPa

cohesion c_p	0.014 MPa
angle of internal friction ϕ_p	34°50′
Young´s modulus E_{def}	0.12 MPa
Poisson´s coefficient ν	0.28

The applied equivalent material is very plastic with a high rate of permanent deformation and on a scale of the model it produced rock of a mudstone type. In order to measure movements of the tunnel lining and surrounding rock needles with small discs at one end facing to the tunnel heading, which serve for non-penetrating of needles to the rock, are installed to the modeled tunnel, see Fig. 1.

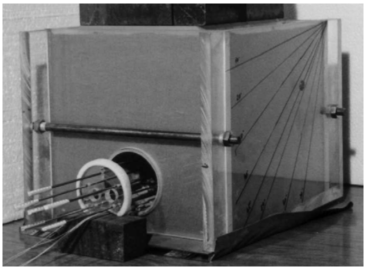

Figure 1: View of the model stand with dimension 250 x 250 x 250 mm equipped by displacement measuring system (needles).

A lined tunnel of cylindrical shape with an internal diameter of 76 mm was modeled parallel to the bottom of stand. To determine stability of the tunnel face in dependence of the length of work-out space, a part of the tunnel lining in the model test was formed from five 20 mm long rings. Among them 2 mm spacing were retained (Fig. 2). These five rings were equipped with locking mechanism, which could be released by using strings. A rubber band, fixed on the external ring circumference, closed the gap in the ring (Fig. 3). During the model experiment, the rings were successively released by a special technology described in the sequel to simulate advancement of the tunnel face. For example, the ring near the tunnel face was released to model starting instant of the excavation of tunnel opening.

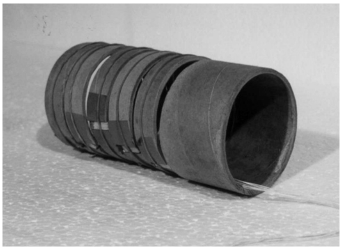

Figure 2: Equivalent of the tunnel lining with inner diameter of 76 mm created by hardened paper used in the model experiment.

As mentioned above, special equipment (based on a system of needles) is developed, which enables one to determine the values of the displacements with the accuracy of 0.05 mm (Fig. 4). Before the experiment tests the needles are lent against the tunnel face. Using a thedolite that is placed about 2 m from the model stand transversaly to the needles, the changes of the position of needles – their displacements due to tunnel face movement – are determined with respect to the initial state of the needles.

Figure 3: One ring used for the tunnel lining forming.

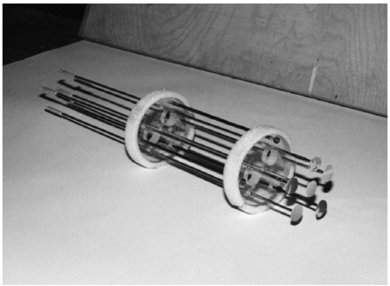

Figure 4: Aluminum needles for tunnel face deformation measurement equipped with square discs.

In Fig. 5 (a) to (e) the contour lines of displacements among the points the needles which are affected by the tunnel face movements, which are measured after successive release of the first to fifth rings of the simulated tunnel lining are shown. The length of work-out space ranges from 22 mm to 110 mm. After releasing the fifth ring the time-dependent behavior of model material is studied. Displacements measured after 50 minutes, 16 hours, 24 hours, 40 hours, 47 hours and 5 days after releasing the fifth ring are shown in Fig. 6 (g) to (k).

5 Conclusions

In this paper the procedure for calculating a laminated arch is suggested in cylindrical coordinates $0r\theta z$, starting with the assumption of generalized plain strain. Before introducing this assumption, the displacements are developed into

WIT Transactions on the Built Environment, Vol 102, © 2008 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)

Fourier's series in the time and hoop coordinates. Employing kinematical equations in cylindrical coordinates, and Hooke's law the stresses are derived in the split formulation, from which the radial and axial coordinates on one hand side and the time and hoop coordinates on the other side are separated. After this variational formulation follows and finite element-like procedure is employed in the coordinate system $0rz$. In radial direction linear approximation of displacements is supposed and in the sense of the generalized plane strain also linear distribution of displacements in axial direction is introduced. Simply supported segment is considered in our case, but more general supports can be involved using given moments at the end points, the clamped edge can be simulated, for example.

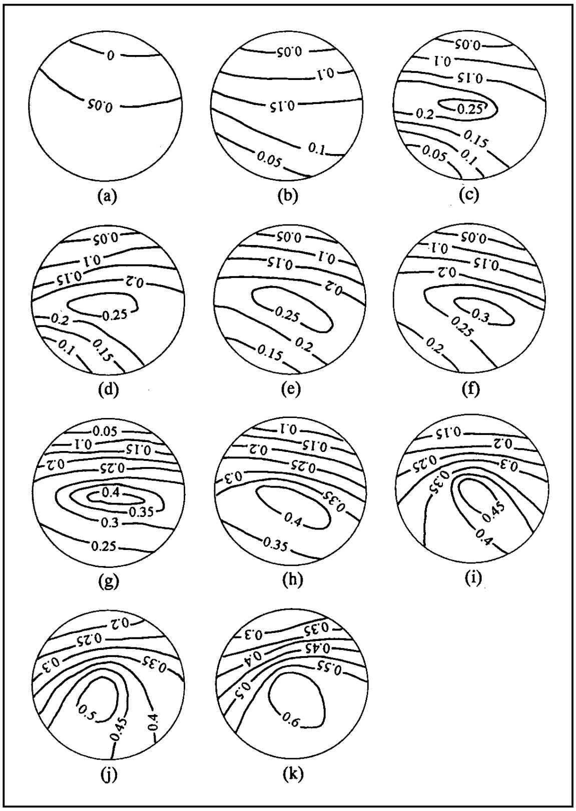

Figure 5: Contour lines of displacements in millimeters measured at the tunnel face during model experiment after simulation of the extended length of the work-out space.

As an example of application of the above described approach a dumping layer for dissipation of energy after application of explosive load is considered in various laminates. Two first natural (eigen) frequencies are observed dependent on the positioned in the structure of the arch. It appears that the most promising case is that, which is defined by positioning the dumper to the outer boundary.

Acknowledgements

This paper was prepared under financial support of GAČR, project No. 103/08/1197. The second and the third authors were partly sponsored by CIDEAS.

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