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# EFFICIENT METHOD OF LOAD CALCULATION FOR UNDERGROUND WORKING SUPPORTS

Summary. The contribution describes the realization of an algorithm for load estimation of an underground support structure applying the method of a contact problem by Kolosov-Muschelischvili. There are stressed the question of modelling the technological influences and is provided the description of all capabilities of programming system TUNKOT.

## SKUTECZNA METODA OBLICZANIA OBCIĄŻEŃ OBUDOWY WYROBISK PODZIEMNYCH

Streszczenie. Opierając się na metodzie Kołosowa-Muscheliszwilego rozwiązywania zagadnień kontaktowych, w pracy przedstawiono algorytm obliczania obciążeń działających na obudowę wyrobisk podziemnych. Zwrócono uwagę na kwestię modelowania wpływów natury technologicznej i podano opis wszystkich możliwości systemu programowania TUNKOT.

## ЭФФЕКТИВНЫЙ МЭТОД РАСЧЕТА НАГРУЗОК КРЕПИ ПОДЗЕМНЫХ ВЫРАБОТОК

Резюме. Опираясь на метод Колосова - Мусхелишвили решения контактных проблем, автор в своей работе представил алгоритм расчета нагрузок, действуюших на крепь подземных выработок. Абтор обращает внимание на проблему моделирования влияний технологическово характера и дает описание всех возможностей системы прогрммирования "ТУНКОТ".

The design and feedback check-up of the underground working's support structure (optimum cross section shape, size and bearing capacity of support, anchor density, phasing of driving and supporting etc.) can be performed using one of the following methods:

1. Empirically, or using results of on-site measurements,
2. Simplifying mathematical model using the rock massif and support working deformation characteristics [1],
3. FEM (BEM) mathematical model [2]; (numerical solution to a contact problem)
4. Analytic solution to a "rock-support" contact problem.

Each of the methods above includes some pros and cons due to the necessary simplifications implied and to capacity to produce models comprehensive of special features of system behaviour, structure of the working and of options for the problem solution.

This paper presents real capabilities of the integrated computation system TUNKOT 2 based on the fourth method group which provide analytical solutions to the "rock-support" system stress /strain problem. The solution is based on the two-dimensional mathematical model of an underground working placed in the initial stress field of the rock massif and described in terms of generally known stress components:

$$\begin{aligned} \sigma_x^{(0)} &= -\gamma h \\ \sigma_y^{(0)} = \sigma_z^{(0)} &= -\lambda \gamma h \end{aligned} \qquad (1)$$

If the support finds itself in full contact with the rock along the breaking's entire circumference, the support load (normal and shear) can be determined from the problem solution with boundary conditions following from the equations:

$$\begin{aligned} u_v = u(\gamma h) - u_0 = \alpha^* u(\gamma h) = u(\alpha^* \gamma h) \\ v_v = v(\gamma h) - v_0 = \alpha^* v(\gamma h) = v(\alpha^* \gamma h) \end{aligned} \qquad (2)$$

where

$u_v$, $v_v$ ... displacements (normal, tangential) of support points in contact with rock

$u(\gamma h)$; $v(\gamma h)$ ... displacements of rock mass points in contact with support

$\alpha^*$ ... factor incorporating technical influences, like initial displacements of the rock mass, changes in support material deformation characteristics in the course of time, bolt and

two-dimensional support combination, displacements having taken place before the heading, differences between real overburden behavior and that as modelled, etc.
The technical factor $\alpha^*$ can be summarized as:

$$\alpha^* = (1 - k) \prod_{i=1}^{i=4} \alpha \qquad (3)$$

$k$ ... deformations having taken place before the heading
$\alpha_{i=1}$ is the influence factor of the hanging subsidence geometry (curve) expressed as in the course of time.
It is determined from:

$$\alpha_{i=1} = \alpha^*_{(t_z\,,\,t)} = \frac{u_t^{(z)} - u_{(t_z)}^{(n)} \left(1 - e^{\beta \frac{t_z}{v_r R}}\right)}{u_t^{(z)}} \qquad (4)$$

where

$t_z$ ... support installation time
$v_r$ ... drifting speed
R ... relevant dimension of working (e.g. width)
$\beta$ ... factor of the hanging subsidence curve geometry
$u_{(t_z}^{(n)}$ ... hanging displacement of the unsupported breaking at time $t_z$

$u_t^{(z)}$ ... hanging displacement of the supported breaking at time $t$

The displacements $u_t^{(z)}$ and $u_{tz}^{(n)}$ are calculated through numerical integration of the equation

$$u_t = \int_1^{R_0} \frac{1}{E_t} \left[ \Delta\,\sigma_\rho(\rho\,,\,t)\left(1 - \mu_t^2\right) - \Delta\,\sigma_\theta(\rho\,,\,t)\,(\mu_t + \mu_t^2)\right] \frac{\delta\,w(\rho)}{\delta\,\rho}\,d\rho \qquad (5)$$

$\sigma_\rho(\rho\,,\,t)$ ... radial stress along the working's vertical axis ( $\theta = 0°$) at time $t$
$\sigma_\theta$ ... tangential stress to the working's vertical axis
$\mu_t$... Poisson's ratio at time $t$
$E_t$... time operator of the rock elasticity modulus
$w_{(\xi)}$... used conformal transformation of the supported hole

$$w_{(\xi)} = R\left(\xi + \sum_{n=1}^{4} g_n \, \xi^{-n}\right) \qquad (6)$$

$g_n$ ... transformation constant

$R_0$ ... point of additional stress due to drifting of the working equal or less than 1 % of the initial stresses

The influence of the built-in support reaction on the hanging displacement is introduced via transforming of the unsupported breaking solution using "substitute" depth.

$$H' = \frac{\gamma H - \sigma_{\rho(t)}}{\gamma} \qquad (7)$$

$\gamma$ ... specific weight of rock
H... actual depth of working
$\sigma_{\rho(t)}$ ... radial stress between support and hanging rock at time $t$

Factor $\alpha_{i=2} = \alpha_{2(t}$ expresses the influence of deformation characteristic variation of support material in time. It is determined by numerical integration of:

$$\alpha_{2(t)} = \frac{\int_{t_z}^{28} t^{-\alpha_h} \left(f_{(t-t_z)} dt + \int_{28}^{t} t^{-\alpha_h} \frac{dt}{1 \frac{\delta_v \, t \, (t}{1 -}}\right.}{\int_{0}^{t} t^{-\alpha_h} \frac{(1-\alpha_v)\, dt}{1 - \alpha_v + \delta_v \, t^{(1-\alpha_v)}}} \qquad (8)$$

for t > 28 days
$\alpha_h$ , $\delta_v$ ... rheologic factors of rock
$\alpha_v$ , $\delta_v$ ... rheologic factors of support material

$$f_{(t-t_z)} = \frac{\sqrt{t - t_z}}{\sqrt{4.2 + 0.85(t - t}}$$

is the function of concrete elasticity modulus growth in time.

Factor $\alpha_{i=3} = \alpha_3$ introduces the influence of hanging bolting on the reduction of vertical displacement thereof. It is determined from:

$$\alpha_3 = \frac{u^k_{(t)}}{u^n_{(t)}} \tag{9}$$

where :

$u^k_{(t)}$ ... vertical displacement of hanging in working with bolting around. The calculation was carried out by numerical integration of equation (5) implicitly comprising deformation parameters of the bolting area.

$u^n_{(k)}$ ... vertical displacement of hanging in unsupported working (see equation (5)).

Factor $\alpha_{i=4} = \alpha_4$ expresses the difference between the behaviour of the geotechnical "infinite weightless half-plane" model characterizing shallow position of working:

$$\alpha_4 = f\left(\frac{H}{D}\right) \qquad \text{for } H / D < 10 - 12$$

$H$ ... depth of working

$D$ ... diameter (width) of working

For the factor's values for various working shapes and depths see Reference [5].

One very important factor entering the calculation is the support's description in terms of homogeneity (homogeneous ring) or inhomogeneity (ring composed of layers with different strain and strength properties). To determine the load to an inhomogeneous ring, the "substitute homogeneous" deformation characteristics $(\overline{E}, \overline{G})$ must be known first. The transformation procedure follows from algorithms for deformations of a homogeneous and inhomogeneous ring of $R$ in radius as per (3). The average parameters and stress adaptation factors for individual layers of an inhomogeneous structure can be obtained through comparison of the displacements of the homogeneous ring and those of the substitute inhomogeneous ring under the same load.

The problem thus formulated will be resolved analytically according to the Kolosov-Muschelishvili method for any shape of breaking using the conformal transformation of the breaking's real cross section on the unit circle. The only limiting condition is that the cross section must be one-axially symmetric [3]. The transformation is through equation (6). Parallel to the contact problem above, verification of whether or not the rock stability condition near the unsupported breaking is realistic. This problem requires to determine the stress/strain conditions near the breaking and to assess whether or not a faulted area will develop. Such integrated system makes it possible to extend the computational power by introducing a number of factors determining the underground working's behaviour from the point of view of the near rock mass (rheology, strength, anchoring influence), support (support material rheology, shrinking, creep), drifting and supporting method (phasing of drifting and support installation, support-to-heading distance, heading impact) and support structure (homogeneous or inhomogeneous support layer, anchoring).

The TUNKOT system's capabilities include:

- Any shape of tunnel cross section (limitation see above) and thickness of lining, calculation of a set of factors for conformal transformation of the working's shape following the change thereof;
- Determining of the stability status of unsupported hole (via size of faulted area calculation) on the basis of the known original stress/strain condition, of rock strength in terms of the strength envelope (linear to trilinear) and of cross section shape. Results make it possible to define the optimum structure of a provisional stabilizing support (see Fig. 1);
- Determining of load status of the working's support under the geostatic stress field (or quasistatic substitution of seismic waves), with any rock deformation parameters and fault density (RQD). The rock can be an elastic or a rheologic matter (use is made of the linear hereditary creep.);
- Any pattern of supporting structure (homogeneous, inhomogeneous (like reinforced concrete), with rigid arcs, etc.) and considering of rheologic properties of concrete (shrinking, creep);
- Use and introducing in the calculation of rock bolting;
- Establishing of models of the lining installation method (impacts of heading, lining-to-heading distance, gradual strengthening of lining) at various stages;
- Testing of whether bolting and lining reaction to the breaking face are sufficient to stabilize the rock in cases of faulted zone in workings without lining ($z > 0.3$ m). The result indicates whether or not lining parameters must be modified;
- Creating of input data files on disc and easy changing of parameters (simplified parametric solutions);
- Result output on screen (print screen option) and formatting of printed output with result evaluation.

Fig. 1 shows a calculation example with some typical graphic output.

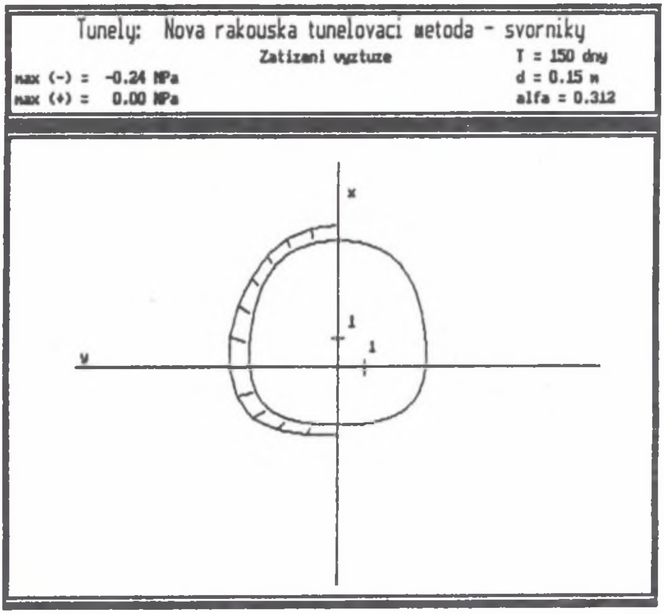


Fig.1. Loading diagram of support

Rys. 1. Wykres obciążeń obudowy;

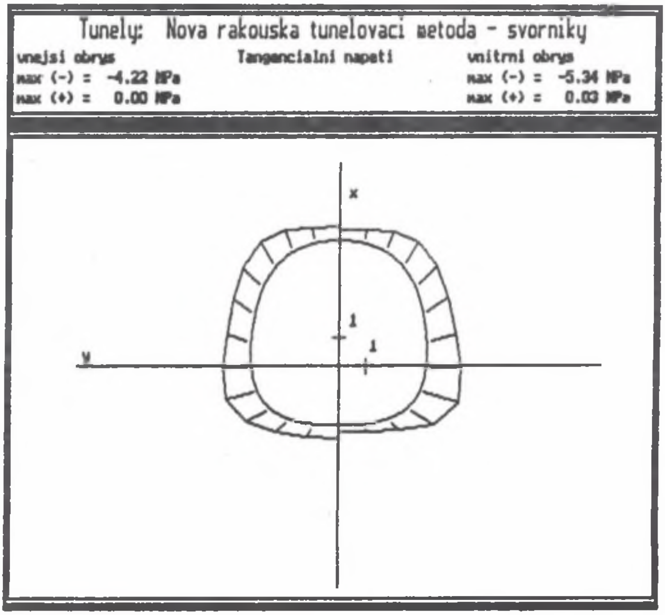


Fig.2. Course of the tangential stresses in the support

Rys. 2. Rozkład naprężeń stycznych w obudowie

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