Stress-strain analysis and global stability of tunnel excavation

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Abstract

This paper shows stress-strain analysis methodology of the tunnel excavation process and applying on two numerous examples from The Main project of hydrotechnical tunnel for hydropower plant Dabar in Bosnia and Herzegovina. Firstly, we perform analysis of the tunnel excavation using of the plane strain assumption of the problem. In tunnel, the stress field are changing when the tunnel face are close. This stress distrubution can be analyzed in 2D model using FEM. In this analysis PAK-finite element program is used and nonlinear analysis is used. To accept underground pressure as consequence of tunnel excavation it has to install primary support (shotcrete, anchors or steel sets). Analysis of the primary support include determination of the support instalation time and type of support. In this phase we considered influence of underground water on tunnel excavation and primary support. In the next step, we perform analysis of stability and calculate safety factor in unsupported tunnel excavations. The method of Shear Strength Reduction is used.

Keywords: tunnel excavation, finite element, stability, primary support, strength reduction.

1. Introduction

This work offers a general methodology survey of the calculation of tunnel excavation and of analysis of a primary support using specific examples of calculation profile from The Main project of the hydrotechnical tunnel for hydropower plant Dabar in Bosnia and Herzegovina.

Chapter 2 offers a survey on theoretic basics and of the way of implementation of appropriate calculations. It particularly gives the survey of excavation and primary support analysis, then the analysis of flow water through ground, and an analysis of global stability of unsupported tunnel excavations using 2D numerical analysis.

In chapter 3 we display concrete calculation examples of the tunnel. Two calculation profiles are displayed, one profile describe rock mass with higher and another with lower mechanical features. Calculations are based on methodology described in previous chapter.

The last chapter gives a general conclusions on methodology and on calculation profiles.

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2. Calculation methodology

Stress-deformation analysis of tunnel excavation is generally a 3D issue, but it may be often analyzed using 2D models, indirectly also introducing 3D effects. Within this work stress deformation analysis is encompassed through next calculations: analysis of the excavations and of primary supports, analysis of the flow fluid (water) through tunnel apperture, and analysis of global stability of unsupported tunnel excavation.

2.1 General postulates on the state of the tension in tunnel excavations

Rock masses are naturally strained and this primary tension states are one of the important features of the surveyed ground. Primary tension state dominantly caused by gravitation, i.e. unit weight of rock and effect of the tectonics. When underground objects are built in rock masses, a new tension state is created, and it is called secondary tension state. Redistribution of primary tension state in rock masses is manifested while excavating an underground room. When the excavation is done, there's always a new state of tension in the zone around the underground structure.

Stress-deformation analysis of tunnel (as linear object whose only dimension is expressed in relation with the other two) is a 3D issue only during a short period of construction (effect of the front of the excavation), because ther tunnel during exploitation is in conditions of state of plane strain.

Let's observe the representative cross-section of the tunnel (cross section A-A on Fig. 1). We define the notion „state of underground room" as the state of the tension, deformities and shifts in rock mass and construction, within cross-section observed. The state of the underground room is the time function and distance of the tunnel face from the cross-section observed. As the tunnel face approaches the cross-section observed, the deformities in the same cross-section increase. And there are two case/situations now. One is stabilization of of the shifts and their tendency towards the final values. In this case there's a possibility not to install support if the shifts are low, and if they are higher, then the support construction should be made, and shift then reach some final value. Another case is when rock masses are of lower mechanical features then the cross section shift starts suddenly increasing when the tunnel face go over the cross section observed, and in that case a primary support is necessary in order to prevent demolition of the tunnel excavation.
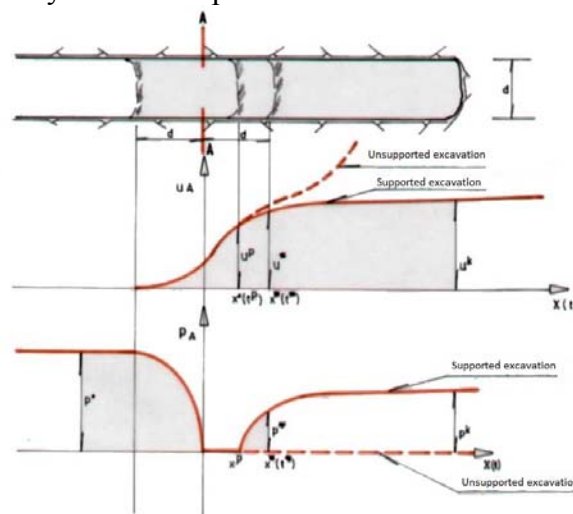

Figure 1. The state of the underground room as the time function and distance of the tunnel face from the cross-section observed

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2.2 Applying FEM for modeling of tunnel axcavation in 2D-numerical analysis

The most common approach to the numeric solving of stress-deformation analysis of non-linnear continuum is the Finite element method (FEM). For the purposes of numeric analysis, a programme package PAK is used [1].

To define mechanical features of rock masses Hoek-Brown criterion is used.

Previously described issue introduction of 3D effects during 2D numeric analysis was made using method of reduction of primary tension state.

Calculation analysis is based on the next: tunnel excavation is placed in primary tension state, then in increments with reduction of 10% decreasing of the values of the tension state up to the value of 0, which represent the situation when the tunnel face is distant from the profile observed.

For every state of the tension in tunnel excavation, a solving tension/deformitiy problem is done, and it produces a characteristic line of the rock which represent the change of the shifts on tunnel excavation due to removal of tunnel face in profile observed.

Based on characteristic line of the rock, we need to determine appropriate type of primary support, as well as the time when the support is being placed. It should be placed when the appropriate shifts already happened, i.e. when the tension around the tunnel rellaxed. To determine the moment to set up the support is done using empirical connections given by Vlachopoulos and Diederichs in [2]. The support can be composed of sprayed concrete and/or anchors and/or steel sets.

2.3 Applying FEM for modeling interaction of solid and fluid

This paper shows analysis of the flow fluid around the tunnel. This type of analysis is not typical for tunnels unless if there is influence of underground water. The hydrotechnical tunnel which considered in this paper, passes through the environment with high underground level. During the year level of water is above the ground very often. In these case it is impossible to excavate tunnel. It can be done when the water drain through the tunnel excavation and it would affect fluid flow through the rock masses around the excavation. This process influences filtration forces which can induce collapse of tunnel. PAK-finite element program is used for this analysis. In the next text we show the equations which describe the interaction between the solid and fluid.

Relation between total stress in material, effective stress and pore pressure is defined by next equation:

$$\sigma_{ij} = \sigma_{ij}' + \delta_{ij} p \qquad (1)$$

Where are: σ_{ij} - total stress tensor, σ_{ij}' - effective stress tensor, p - hydrostatic pressure and δ_{ij} is Kronecker delta symbol.

The equilibrium equation of the mixture is [3]:

$$\sigma_{ij,j} - \rho \ddot{u}_i - \rho_f \ddot{w}_i + \rho b_i = 0 \qquad (2)$$

whtere are: $\ddot{u}_i$ - acceleration of the solid part, $\ddot{w}_i$ - relative acceleration of the fluid, b_i - body forces per unit mass, ρ_f and ρ - density of the fluid and mixture respectively.

The equilibrium equation of the fluid is written as:

$$-p_{,i} - R_i - \rho_f \ddot{u}_i - \frac{\rho_f \ddot{w}_i}{n} + \rho_f b_i = 0 \qquad (3)$$

where are: R_i - viscous drag forces , n - porosity of the solid .

Flow conservation equation is defined as:

$$\dot{w}_{i,i} + \alpha \dot{e}_{ii} + \frac{\dot{p}}{Q} = 0 \qquad (4)$$

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Where are: α - parameter ($\alpha = 1 - K_t/K_s \approx 1$), e_{ij} - strain inkrement of the solid part, p - pore pressure ,Q - compressibility of the fluid and solid.

Using the Eq. (2), Eq. (3) and Eq. (4) numerical forms of governing equations can be written in the matrix form [4]:

$$\begin{pmatrix} M_s & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & M_f \end{pmatrix}\begin{pmatrix} \ddot{u} \\ \ddot{p} \\ \ddot{U} \end{pmatrix} + \begin{pmatrix} C_1 & 0 & -C_2 \\ 0 & 0 & 0 \\ -C_2^T & 0 & C_3 \end{pmatrix}\begin{pmatrix} \dot{u} \\ \dot{p} \\ \dot{U} \end{pmatrix} + \begin{pmatrix} K^{EP} & -G_1 & 0 \\ -G_1^T & -P & -G_2^T \\ 0 & -G_2 & 0 \end{pmatrix}\begin{pmatrix} \bar{u} \\ \bar{p} \\ \bar{U} \end{pmatrix} = \begin{pmatrix} \bar{f}_s \\ 0 \\ \bar{f}_f \end{pmatrix} \quad (5)$$

Where are: u - displacement of the solid , p - pore pressure ,U - displacement of the fluid.

Eq. (5) represent the general form of $u - p - U$ formulation for coupled system of solid and fluid.

2.4 Applying FEM for analysis of global stability of tunnel excavation

Analysis of global stability is based on the method of shear strength reduction (The Shear Strength Reduction) which allows the application of the finite element method and Hoek-Brown criterion of material (or other material model), determine the factor of safety of the rock mass [5].
The SSR form of analysis involves the following steps:
1. Reduction of the shear strength envelope by a factor F
2. Determination of new strength model parameters that correspond to the redusced envelope
3. Use of the new parameters in new stress-strain analysis on same model FE.
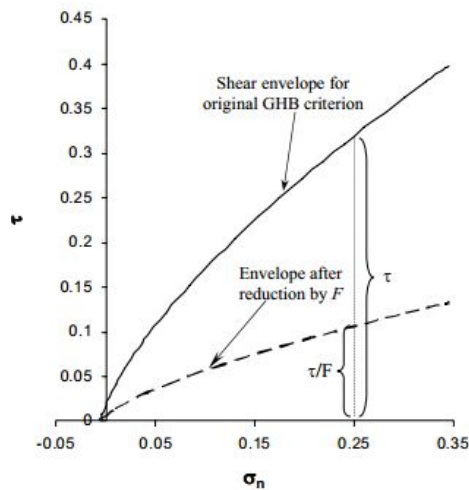This algorithm is incorporated into the PAK.

Figure 2. Generalized Hoek-Brown criterion curve, and the resulting curve when the envelope is reduced by a factor F

The safety is checked for the next situations:
- Unsupported excavation without underground water
- Unsupported excavation with influence of flow water

Factor of safety is the highest value for the reduction factor F which is obtained by the tunnel excavation is stable. As a criterion for instability (occurrence of fracture) takes the situation when the numerical calculation can not converge to a solution.

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3.   Applying described methodology for calculation of tunnel

As examples of which was carried out described calculation methodology of tunnel excavation are displayed two numerous examples from The main project of hydrotechnical tunnel for hydropower plant Dabar [6]. The first example applies to the rock masses with better mechanical characteristics, where primary support is not provided, and the second example is applies to the weak rock masses, where primary support is necessary.

3.1 Numerous example 1

Parameters of material which define rock mass in Example 1 are showed in the next table. On the Fig. 3 is showed characteristic curve of rock as defined in heading 2.2. The ground of elevation measuring from axis of tunnel is 130 m. The level of underground water is 35 m.

Table 1. Parameters of material

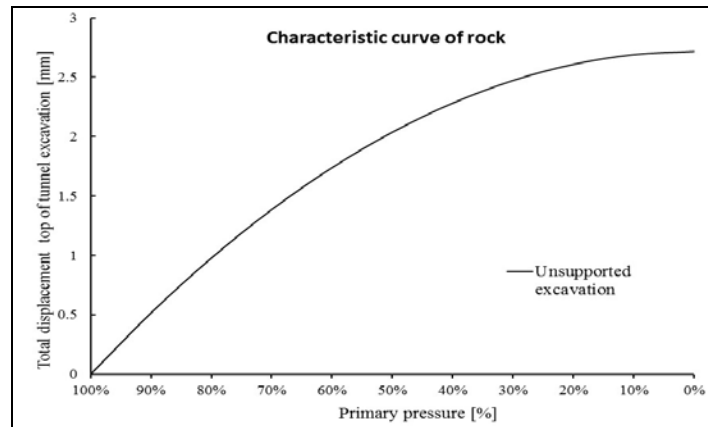| GSI-Geological Strength Index	60
Young's Modulus (MPa)	7500
Poisson's ratio	0,24
Intact Compresive Strength (MPa)	50
Intact Rock Constant mi	17
Coefficient of permeability (m/s)	2×10^{-7}

Figure 3. Characteristic curve of rock in the first example

It could see from Fig. 3 that maximum total displacement of top of tunnel excavation is 2,7 mm for case when the tunnel face is far from observed profile. Also we can see that total displacement tends asymptotically finally value, that means it doesn't have any dangerous about collapse of tunnel excavation.
Numerous value of factor of global stability for unsupported excavation is: 1,56.
Numerous value of factor of global stability for unsupported excavation when it occurs filtration forces is: 1,45.
The field of total displacement and flownet filtration forces are displayed in the next pictures:
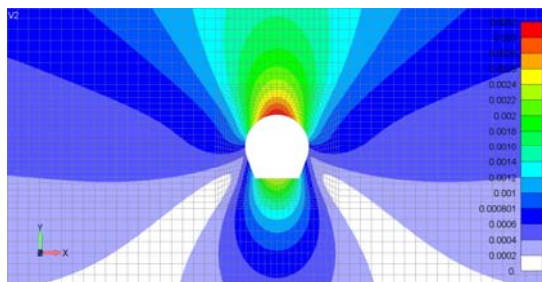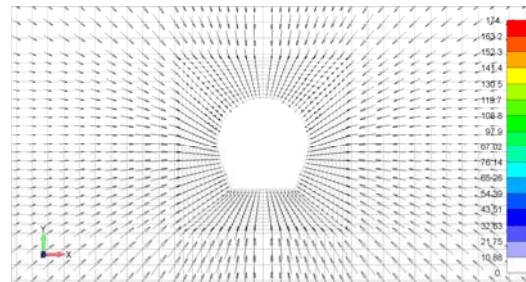

Figure 4. Total displacment

Figure 5. Flow net of filtration forces

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Maximum total displacement of top of tunnel excavation when it occurs filtration forces is: 3,2.
From all the observed previosly, we can conlude that there is no danger of collapse of tunnel excavation, so it is not necessary to install the computational support.

3.2 Numerous example 2

Parameters of material which define rock mass in Example 2 are showed in the next table. On the Fig. 3 is showed characteristic curve of rock. The ground of elevation measuring from axis of tunnel is 65 m. The level of underground water is 36 m.

Table 2. Parameters of material

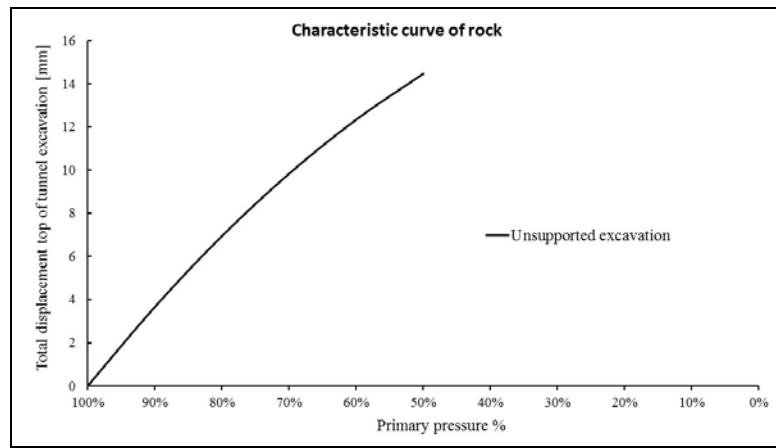|	
GSI-Geological Strength Index	35
Young's Modulus (MPa)	1000
Poisson's ratio	0,29
Intact Compresive Strengt (MPa)	35
Intact Rock Constant mi	12
Coefficient of permeability (m/s)	$6,2 \times 10^{-6}$

Figure 6. Characteristic curve of rock in the second example

The Fig. 6 shows that the movement of the contour of the excavation does not tend final values as the internal pressure reduces, which indicates that during the removal of the tunnel face the movement of the contour of the excavation progressively increases and may lead to the collapse of the tunnel excavation if it is not performed primary support.
Maximum displacement, which is obtained in the last stage before the collapsse in the rock mass is about 15,0 mm (Fig. 6).
In the presented analysis provided the values of the global factor of safety is less than 1. Rock mass is not able to achieve balance coating the outer ring, so that includes installation of the primary support immediately after the tunnel face passed the observed profile.
Assume the characteristics of the primary support:
   • Shotcrete thickness 30 cm.
Installation of primary support when the tunnel face passed the observed profile (at internal pressure of 60% in the numerical model).

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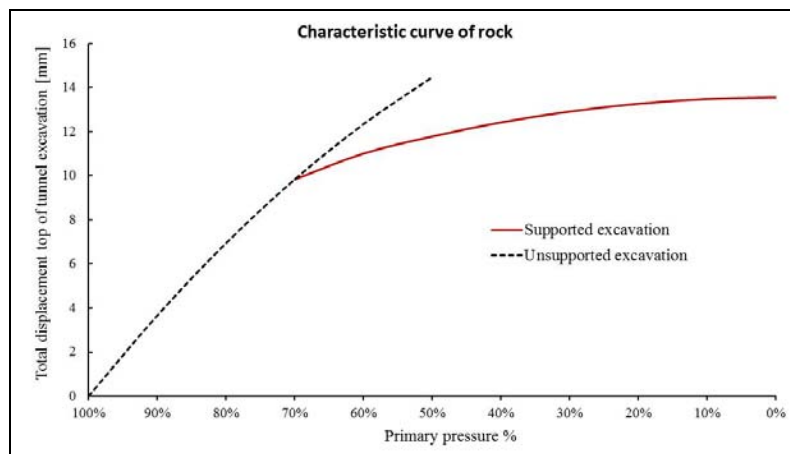CE-PhD 2014, 10-13 December 2014,Cluj-Napoca, Romania
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Figure 7. Total displacement top of tunnel excavation

The Fig. 7 shows how to develop movement of tunnel excavation after installation of the primary support, which shows that after the installation of support, movement is stabilized and tends asymptotically final value. Values of axial forces and bending moments are obtained for two situation as follows:

1) The case where there is only the influence of undergorund pressure:

The section of top of the tunnel: Axial force = 2204 kN Moment bending=95,42 kNm

2) The case where, despite the impact of undergorund pressure exist and influence of filtration forces acting on the structure.

The following figure shows plots of the horizontal and vertical stresses in the concrete lining:
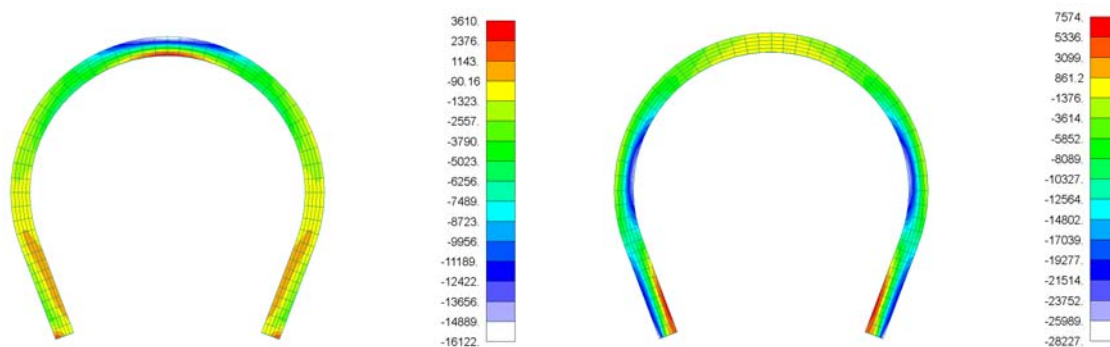

Figure 8. Horizontal and vertical stresses in shotcrete

By integrating the stresses gain values force the sections of tunnel lining. The greatest impacts occur at the top of the the tunnel:
Axial force = 3061 kN Bending Moment =108,25 kNm
As described previously, when designing the concrete support and determining the reinforcement load combination causing both the filtration forces and the ground pressure should not be neglected. Determine the required reinforcement is done according to the applicable regulations for dimensioning, which is not the subject of this paper.

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4. Conclusions

This paper described the methodology of calculation for tunnel excavation with examples from Main project of hydrotechnical tunnel for hydropower plant Dabar in Bosnia and Herzegovina. Tunnel excavation, flow water in rock masses, installation of primary support and analysis of global stability of unsupported tunnel excavation were considered. The methodology which is described in this paper is based on modern principels design tunnels in finite element method. The interaction between the solid and fluid as coupled influence of solid and fluid was analyzed, because there is flow water through rock masses. This calculation is necessary since there is a high level of underground water which could influence collapse of tunnel excavation caused by the filtration forces which are additional load beside underground pressure on tunnel. Global stability analysis gives a general view of load-bearing reserve for unsupported excavation, and engineers get a higher level of safety when they make decisions about primary support. This type of analysis which is performed here is based on strength reduction of material, commonly used for stability of slopes. We can apply these kind of analysis on tunnels where there is excavation in phases and strength reduction has to go through all phases of excavation.

It should be noted that tunnels are more specific in structure analysis than other structures, because there are many independent parameters that are necessary for stress-strain analysis. These parameters are based on various assumptions and experiences and small numerous *in situ* tests. Therefore, structural engineers have to analyse these structures with higher level of safety.

The procedures and analysis displayed in this paper are opened for upgrade in the phase of building the structure, because in this phase the information about measuring and mapping of ground will be available and it can be used for numerical models. Parameters of material, as the most important information, will be calibrated and determined the parameters which correspond to the real behaviour of observed rock mass in situ. Finally, used primary support and determination of global stability of structure will be verified.

5. References

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