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Time influence of tunnel support on the factor of safety

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Abstract. Before taking any measures to build a tunnel, the rock (soil) is in a primary stress state, which means that the stress state is a function of the thickness of the overburden. At the moment when the measures necessary to excavate a tunnel are taken, the rock state changes from primary to secondary, leading to stress concentration, especially in the tunnel abutments. If the rock is capable of accepting these stresses, a state of equilibrium is reached after certain deformations. Plastic deformations can occur if the stresses are larger than the strength of the rock mass. To avoid excessive deformations or collapse of the rock and the tunnel excavation, it is necessary to place a support. The achieved factor of safety is a function of both the support type and the time when the support is installed. This paper shall present a numerical example of different pressures considered in order to obtain the rock's reaction curve.

1 Types of tunnel supports

Different materials, collectively known as support (lining, reinforcement), are used to achieve stability of the excavated tunnel. These materials should be installed at a certain time interval following the excavation, to avoid the collapse and closing of the tunnel. The applied support can be of 4 types, depending of the mode of influence:

- Shotcrete (sprayed concrete), individually or in combination with light steel sets (arches), provides safety through stabilization or supporting of the rock mass;

- Anchors (rock bolts) as a support type act as a reinforcement in the rock mass, which provides the stabilization of the excavation;

- Steel sets (arches), shields, prefabricated elements or similar, are used for supporting of the rock mass;

- Support types that consolidate the rock mass and improve its geotechnical characteristics. These include compressed air, freezing and consolidating grouting.

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2 Deformations of the rock masses – reaction curves

The behaviour of most rocks is not ideally elastic (Hoek's body), therefore, it is necessary to consider the stresses according to the plasticity theory. Pursuant to this theory, three zones occur around the tunnel (excavation) opening:

- Stress-free zone – directly around the opening;
- High-pressure zone – zone of the bearing ring located inside the rock;
- Undisturbed zone – located at a certain distance where there is no influence from the excavation.

The strength of the necessary support (Po) can be defined as depending on the length of the plasticity radius (Rpl), which defines the size of the plasticized zone (figure 1).

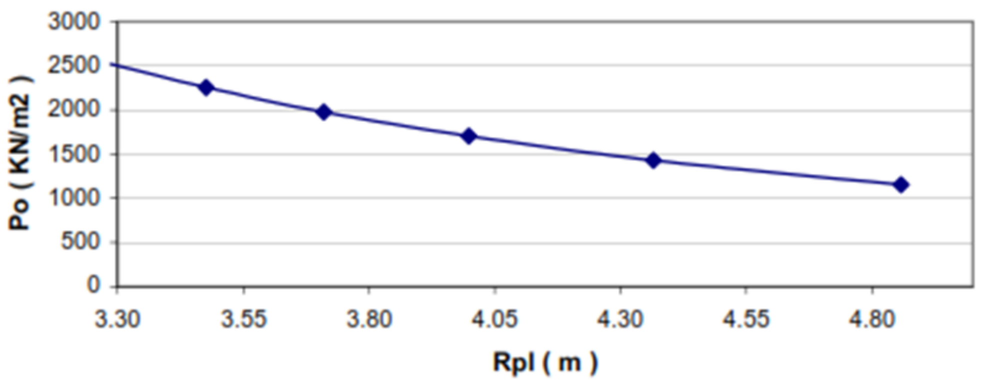

Fig. 1. Dependence between the strength of the support (Po) and the plasticity radius.

This diagram indicates that the bigger the plasticity radius is, the lower the strength of the support should be. This is a result from the deformations incurring upon the increase of the plasticized zone. With the increase of the plasticity radius, convergences (displacements - Ua) also increase, hence the strength of the support that has the purpose of preventing these displacements will be lower.

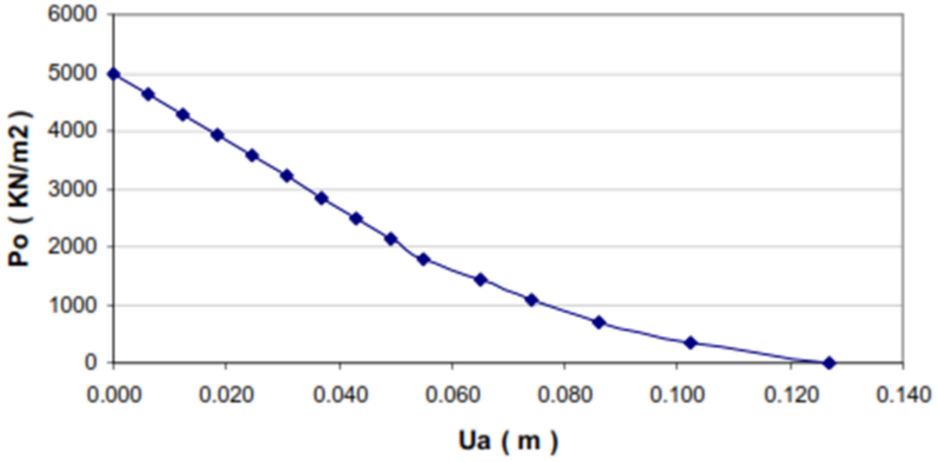

Fig. 2. Dependence between the convergences (Ua) and the support strength (Po).

If a circular tunnel with a radius of r_0, prone to hydrostatic pressure of p_0, is considered, and the support pressure is p_i (as shown on Figure 3), the collapse of the rock mass around the tunnel is expected to incur when the support pressure of p_i is lower than the critical pressure of p_{cr}.

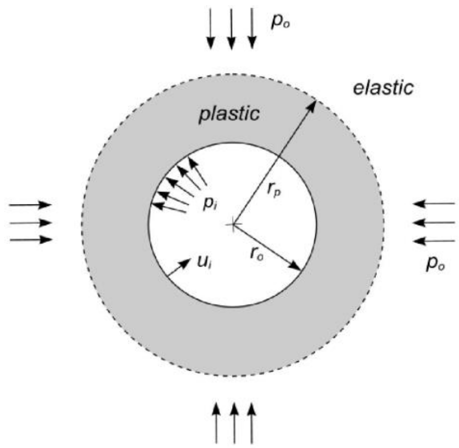

Fig. 3. Plastic zone surrounding a circular tunnel.

In order to obtain the reaction curve it is necessary to define the dependence between the support pressure and the radial displacements (p_i and u_i). It was supposed that at the tunnel face, the rock provides for initial support pressure equal to the on-spot pressure (in-situ) of p_0. With the advancement of the tunnel face, the pressure decreases, reaching the zero value at one point. With this type of dependence, the reaction curve presents elastic, plastic and zero convergences (figure 4).

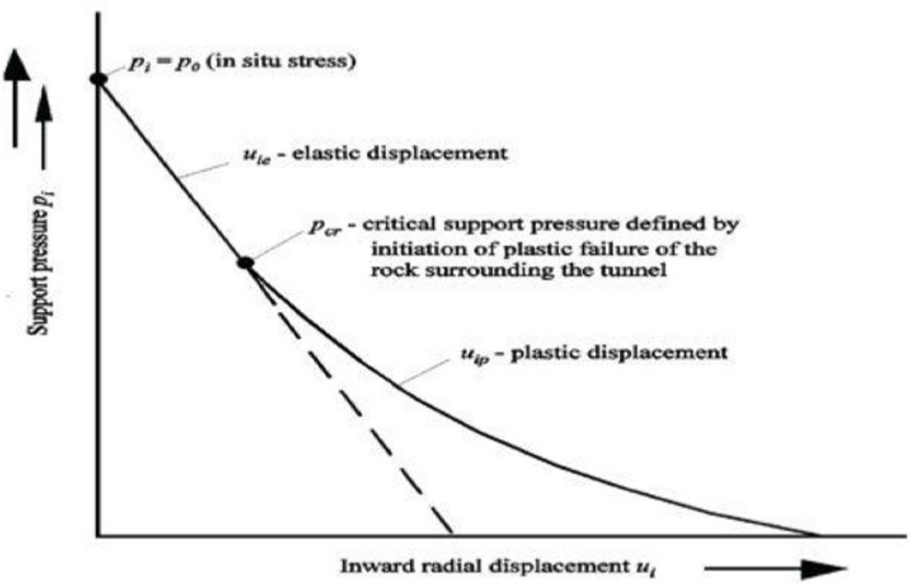

Fig. 4. Typical ground reaction curve.

The support reaction curve depends on three key factors:
- Convergence of the tunnel walls before the installation of the support;
- Support stiffness;
- Support bearing capacity.

3 Numerical example

In order to obtain the support reaction curve and the rock displacement curve, the following was considered: a rock of IV category according to Bienawski, with RMR = 38; c = 0,653 MPa; φ = 38,39 °. The Poisson's coefficient is estimated at ν = 0,3. The support envisaged for these conditions does not change in the calculations. The adopted radius is r_o = 5,0 m. In this case, the pressure of p_0 is taken as hydrostatic pressure ($p_0 = \gamma$*H) and is calculated according to the Heim's theory. The obtained value is p_0 = 5,2 MPa.

Using Hoek approach for tunnels in weak rock, the given example considers different pressures, in order to obtain the rock reaction curve. An appropriate plasticity radius (r_p) and initial displacement (u_i) has been obtained for each of these pressures (table 1).

Table 1. Results of the plasticity radius and the initial displacement.

p_{i0} (Mpa)	5,20	r_{p0} (m)	3,854498	u_{i0} (m)	0,005383
p_{i1}(Mpa)	3,00	r_{p1} (m)	4,529562	u_{i1} (m)	0,005912
p_{i2} (Mpa)	1,46	r_{p2} (m)	5,556997	u_{i2} (m)	0,008600
p_{i3} (Mpa)	0,70	r_{p3} (m)	6,744459	u_{i3} (m)	0,013368
p_{i4} (Mpa)	0,00	r_{p4} (m)	11,33518	u_{i4} (m)	0,042955

These calculations make it possible to construct a reaction curve - the p_i – u_i diagram. This diagram consists of two parts – a linear part (where the displacements are elastic) and a non-linear part (where plasticity radius and plastic displacements incur). For the given rock, a sprayed concrete support, 1500 mm thick and anchors of φ25 mm, at the longitudinal and transversal distance of 2 m has been adopted. The relation between the pressure and the stiffness of the adopted support is p_{smax}/Ks = 0,024.

In order to obtain the support reaction curves it is necessary to review the tunnel convergence for different values from the tunnel face (table 2).

Table 2. Results for the displacements depending on the distance from the tunnel face.

x_1	-10	u_1/u_{im}	0,036761	u_1	0,00048787	u_{y1}	0,024547
x_2	-5	u_2/u_{im}	0,099927	u_2	0,001326167	u_{y2}	0,025385
x_3	-1	u_3/u_{im}	0,222393	u_3	0,002951438	u_{y3}	0,02701

x_4	0	u_4/u_{im}	0,271631	u_4	0,003604894	u_{y4}	0,027664
x_5	0,5	u_5/u_{im}	0,347448	u_5	0,004611086	u_{y5}	0,02867
x_6	1	u_6/u_{im}	0,415373	u_6	0,005512544	u_{y6}	0,029571
x_7	2	u_7/u_{im}	0,530749	u_7	0,007043722	u_{y7}	0,031103
x_8	5	u_8/u_{im}	0,757346	u_8	0,01005097	u_{y8}	0,03411
x_9	10	u_9/u_{im}	0,919161	u_9	0,012198458	u_{y9}	0,036257
x_{10}	15	u_{10}/u_{im}	0,973069	u_{10}	0,012913886	u_{y10}	0,036973
x_{11}	20	u_{11}/u_{im}	0,991028	u_{11}	0,013152228	u_{y11}	0,037211

In order to construct the support reaction curves it is necessary to determine the displacement u_{iy} that will depend on the type and the stiffness of the adopted support.

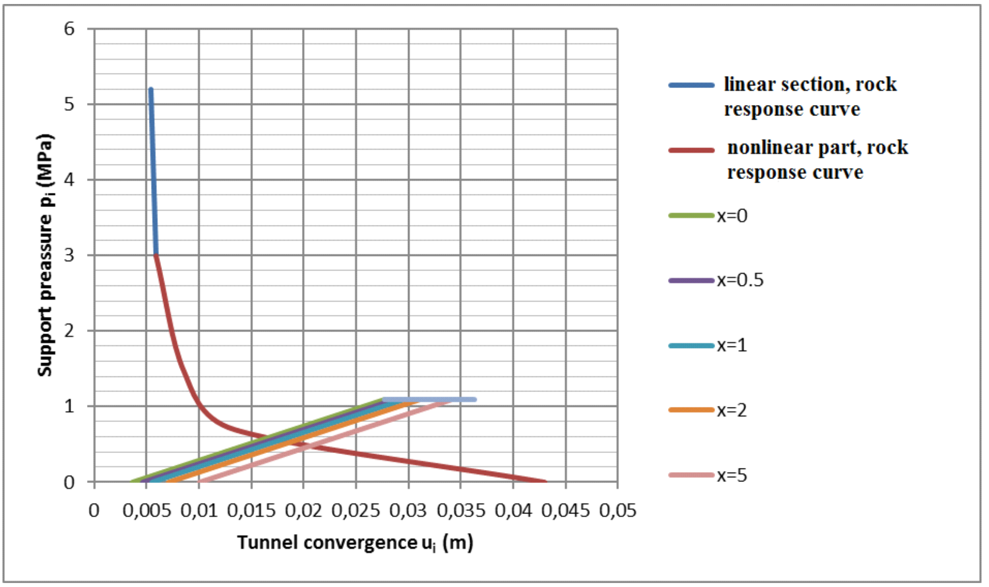

Fig. 5. Reaction curves for different distance from the tunnel face.

The support pressure values obtained from the diagram (figure 5) are then used for the calculation of the equilibrium pressure (p_{se}) and the factor of safety (FS). Equilibrium pressure is the pressure under which the displacement of the rock and of the support would be equal. The factor of safety is fraction between the maximum (p_{smax}) and equilibrium support pressure (table 3).

Table 3. Results for the factor of safety.

p_{se1} (Mpa)	0,62	p_{max} (Mpa)	1,0956	FS_1	1,7671
p_{se2} (Mpa)	0,57			FS_2	1,9221
p_{se3} (Mpa)	0,55			FS_3	1,9920
p_{se4} (Mpa)	0,52			FS_4	2,1069
p_{se5} (Mpa)	0,42			FS_5	2,6085

4 Conclusion

In order to ensure the stability of the excavated tunnel it is necessary to install the appropriate support. The support is characterized by adequate bearing capacity and stiffness, primarily depending on the features of the rock mass into which the tunnel is constructed. Anchors, steel sets, sprayed concrete and final concrete linings are the most used support elements (materials). Each of these materials can be used individually, but they are most frequently combined. Besides the type of support, the time of installation also plays an important safety role. The increase of the initial displacements reduces the equilibrium pressure (the pressure necessary to equalize the rock displacements and the support). This results in an ever-higher factor of safety. The factor of safety of FS = 1,92 has been obtained for the distance of x = 0,5 m from the excavation front whereas the distance of x = 2,0 m resulted in FS = 2,11. It is, therefore, better to allow for certain convergence before the support is installed. However, the maximal allowed displacement must not be exceeded as it can lead to collapse of the rock.

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