Support of an Underground Opening

The presented stability analysis refers to monolithic rock, to monolithic blocks between joints. Naturally, it is also necessary to perform an analysis of the structural instability of the excavated opening. One must identify the blocks along the perimeter of the opening that have a kinematic possibility to slide into the void, assess their stability, and propose measures for their stabilization. Stable rock blocks and the joints that form them around the opening do not influence the presented stability analysis—**except** in the case of rocks with planar structure, where the planes are perpendicular to the direction of the minimum principal stress. In such a case, the tensile strength differs in two directions, and this must be determined and taken into account.

The favoring of the term "rock mass" in the last few decades has led things in the wrong direction. The deformation modulus of the rock mass, the stress of the rock mass, and the strength of the rock mass are—at best—misleading terms.

It is the monolithic blocks that make up the mass which are stressed. Portions of the mass without cohesion—or material without cohesion—cannot be stressed. After the excavation of the opening, the most unfavorable stress state in terms of the potential for tensile crack formation is along the perimeter of the opening. Fracture begins at critical locations on the perimeter of the opening, and the condition of the rock mass further from that point has no effect on it. Existing joints may facilitate the fallout of newly formed fractured fragments, but they do not influence their formation.

This discussion addresses an underground opening of the tunnel type (large length relative to cross-sectional area). Let us suppose the opening is excavated in hard rock using blasting. The opening is excavated discontinuously, in segments whose length is on the order of the tunnel diameter.

From a safety perspective, the following situations are possible:

- The ratio of induced tensile stress and the tensile strength of the rock is such that the opening is stable the entire time, i.e., the induced tensile stresses are lower than the rock's tensile strength.

- The opening is never stable at any moment. Not even the shortest rational advance ensures stability. In such a case, special excavation methods are used, which we will not discuss here.
- The opening is unstable in the zone of plane strain and cannot exist without support, but at a certain distance from the face it has some stability.

In modern mining practice, two main support methods are generally used:

Support using anchors, Support using surface lining with shotcrete or cast concrete. Combined methods of support utilize both of these approaches, often in combination with steel mesh or sometimes with steel frame supports.

When excavating a tunnel-like opening, the initial part—from the face to a length equal to the “diameter” of the opening—has its principal stress distribution influenced by the tunnel face. More precisely, the intensity of the minimum principal stress varies, and consequently the tensile stresses in the rock along the perimeter of the opening vary as well, as previously explained in the "Stability Analysis."

$$\sigma_t = st \cdot \sigma_1 - \sigma_3$$

We now introduce the concept of effective minimum principal stresses ($\overline{\sigma_3}$). As already explained, under the influence of maximum principal stresses (σ_1), particle "C" pushes particles "A" and "B" apart—i.e., pushes particle "A" toward the void. This movement is opposed by the minimum principal stresses (σ_3), as shown in Figure 1. Particle “A” is the last particle beneath which there is void; particle “A′” is adjacent to it, beneath which are other particles. Particle “A” moves downward, while particle “A′” remains stationary. This causes friction between the two particles, and the frictional resistance to the movement of “A” is:

$$\sigma_{td} + (\sigma_{td} + \sigma_2) \cdot tg\varphi$$

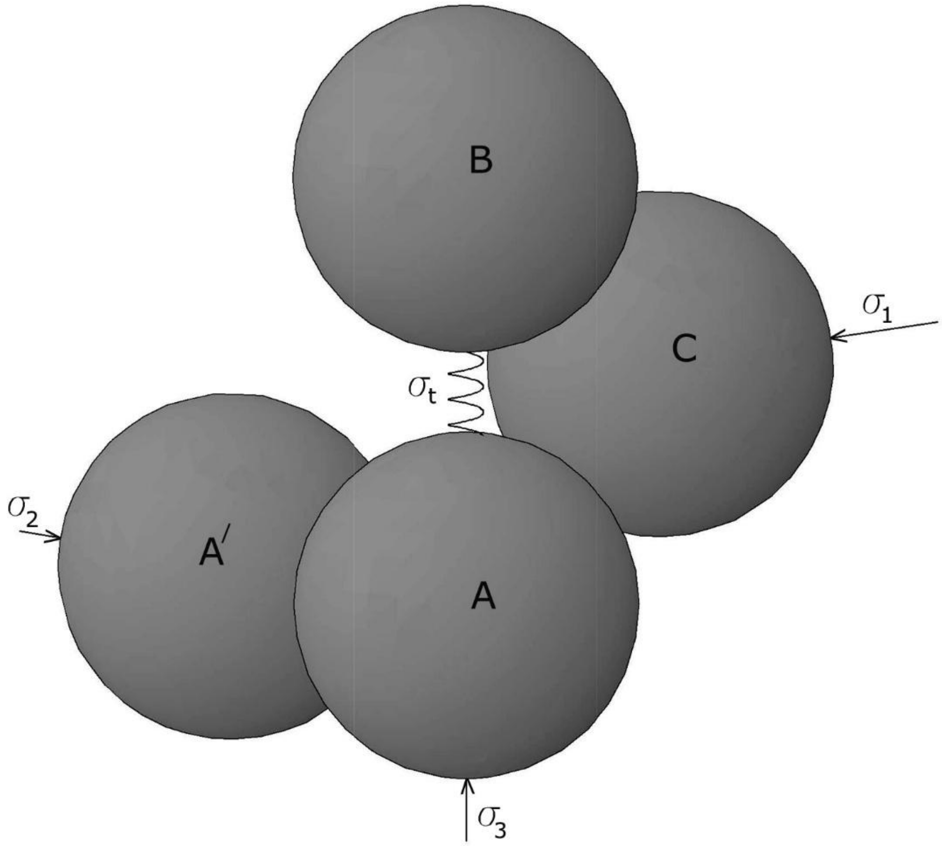

Figure 1. Influence of the tunnel face on the intensity of tensile stress

The allowed value of tensile stress here is the tensile strength or cohesion. Thus, the effective minimum principal stresses ($\overline{\sigma_3}$) are:

$$\overline{\sigma_3} = \sigma_3 + \sigma_{td} + (\sigma_{td} + \sigma_2) \cdot tg\varphi$$

This means that tensile stresses in the rock along the perimeter of the opening near the face are:

$$\sigma_{ts} = st \cdot \sigma_1 - \overline{\sigma_3}$$

At a distance equal to the "diameter" of the opening (D), the plane strain condition is established.

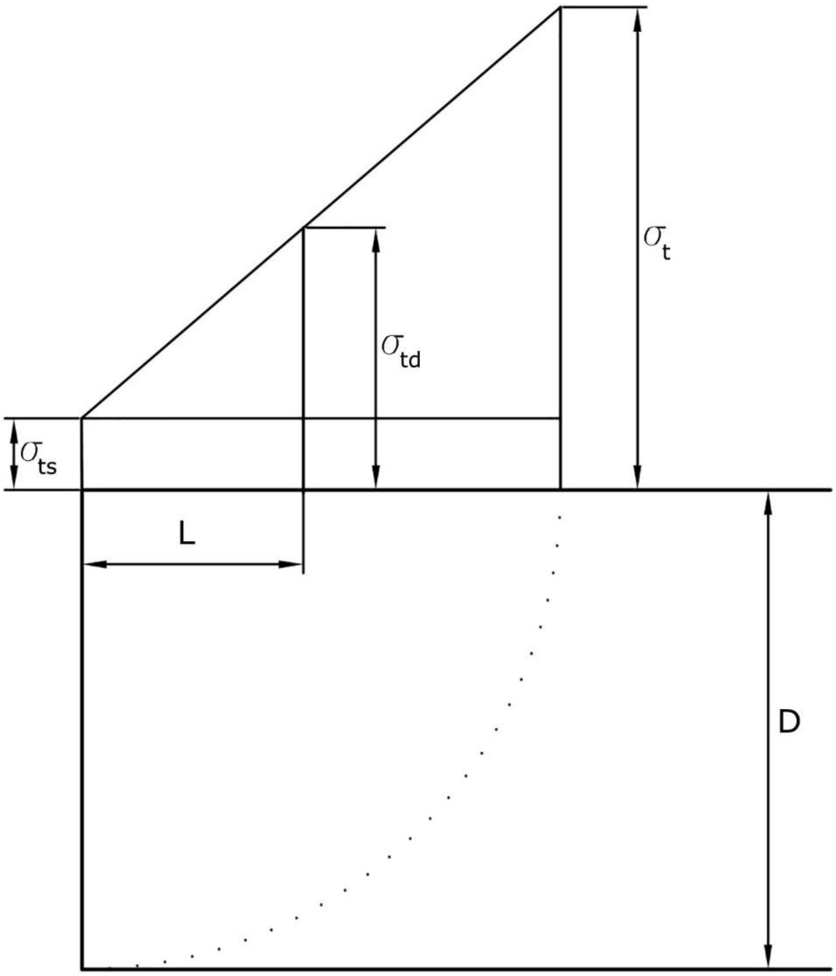

Figure 2. Determining the unsupported tunnel length

To determine the maximum length of unsupported tunnel at which the tensile stresses at critical locations in the perimeter rock do not exceed the fracture limit, proceed as follows: Using a numerical model (e.g., finite element method), for a given profile, determine the magnitude of the induced maximum and minimum principal stresses (σ_1, σ_3), based on initial stress state data of the rock mass ($\sigma_v, \sigma_H, \sigma_h$). Using rock parameters—the internal friction angle (φ) and Poisson's ratio (ν)—calculate:

$$st = \frac{\nu}{1 + tg\varphi}$$

Then calculate the value of the tensile stress:

$$\sigma_t = st \cdot \sigma_1 - \sigma_3$$

If the tensile stresses in the rock along the perimeter (σ_t) exceed the allowable tensile stress (σ_{td}), determine the distance from the tunnel face (L) where induced tensile stresses will equal or fall below the allowable tensile stress ((σ_{td}):

Then recalculate the effective minimum principal stress at that location:

$$\overline{\sigma_3} = \sigma_3 + \sigma_{td} + (\sigma_{td} + \sigma_2) \cdot tg\varphi$$

And:

$$\sigma_{ts} = st \cdot \sigma_1 - \overline{\sigma_3}$$

As shown in Figure 2, the unsupported tunnel length from the face (L) can be calculated as:

$$L = D\frac{\sigma_{td} - \sigma_{ts}}{\sigma_t - \sigma_{ts}}$$

It should be noted that the safety factor is not included here. Those who have solved these problems using numerical models know that this dependency is not linear, and that the transitional zone is longer than the tunnel diameter, but beyond this distance, changes are minimal, and within this distance, a linear relationship suffices for practical calculations.

The next and key question is: how to ensure that the already excavated opening remains stable after the next segment is excavated, and later as well. This is achieved by reinforcing the rock along the perimeter of the opening. The rock fractures when the tensile stress exceeds the failure limit. Therefore, the tensile strength of the rock must be increased. This can be achieved in two ways:

- By installing anchors into the rock along the perimeter of the opening. The direction of the installed anchors is the same as the direction of the minimum principal stresses. The anchors used have low bearing capacity, on the order of 0.1 to 0.3 MPa. If the missing tensile strength of the rock is 1–3 MPa, it is necessary to install about ten anchors per m². But what if the missing rock strength is significantly greater? Anchors of "high bearing capacity" are required. Anchors are suitable for stabilizing blocks that have a kinematic possibility to slide into the void, that is, for solving structural instability.
- By installing (adding) an artificial rock mass made of cast or sprayed concrete of appropriate thickness and appropriate tensile strength. This artificial mass is called a concrete lining.

Dimensioning of the Concrete Lining

If the required tensile strength is less than that of ordinary cast concrete or sprayed concrete, the problem will be solved very simply. It is generally accepted that sprayed concrete is not installed in thicknesses below 3 cm. Therefore, sprayed concrete of 3 cm thickness will resolve the stability problem. Whenever possible to solve the problem using sprayed concrete, cast concrete should not be used—unless specific structural reasons exist. Support using cast concrete will be much more expensive, will take considerably longer, and the effects will be the same.

If the missing tensile strength is greater than that available, the concrete structure must be reinforced with a sufficient number of steel bars placed in the direction of the minimum principal stresses. The thickness of the cast concrete should be the minimum technological thickness that ensures proper installation of quality concrete with appropriate steel reinforcement.

It is not the thickness of the concrete lining that matters, but its tensile strength in the direction of the minimum principal stresses.

Large thickness of concrete with insufficient tensile strength is meaningless. Quantity cannot replace quality.

Sprayed concrete can be reinforced with fiber, and if that is not sufficient, an appropriate reinforcement frame can be installed on the wall before the concrete is applied.

We will once again use the simplest model: an underground opening with circular cross-section and all three components of the primary stresses having the same intensity ($\sigma_1 = 10MPa$, $\sigma_2 = 10MPa, \sigma_3 = 10MPa$). The loading is divided into two parts: The first part of the load is applied at the moment when a segment of the opening is excavated and is still stable. Then, the sprayed concrete support is installed. Then, the remaining load is applied (corresponding to the plane strain condition).

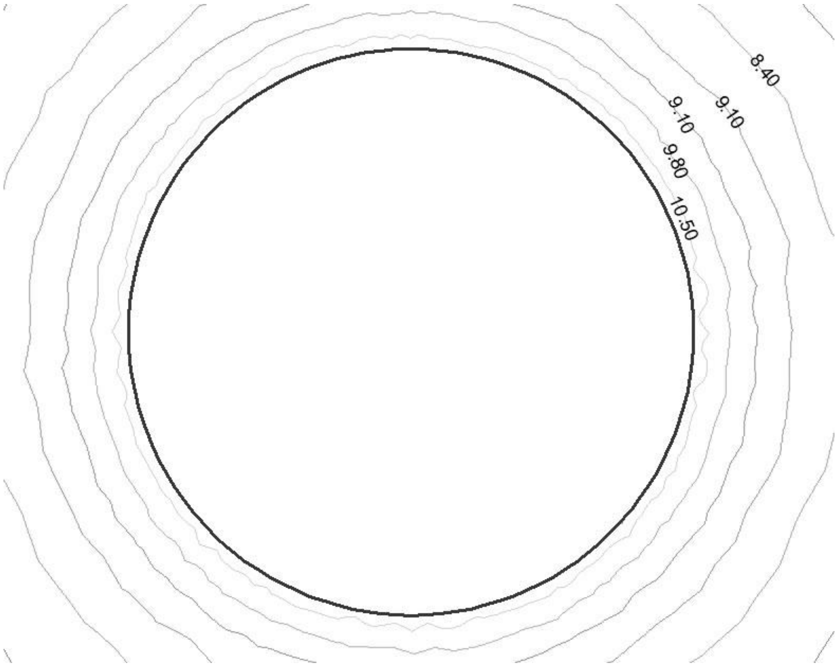

Figure 3. Maximum principal stresses

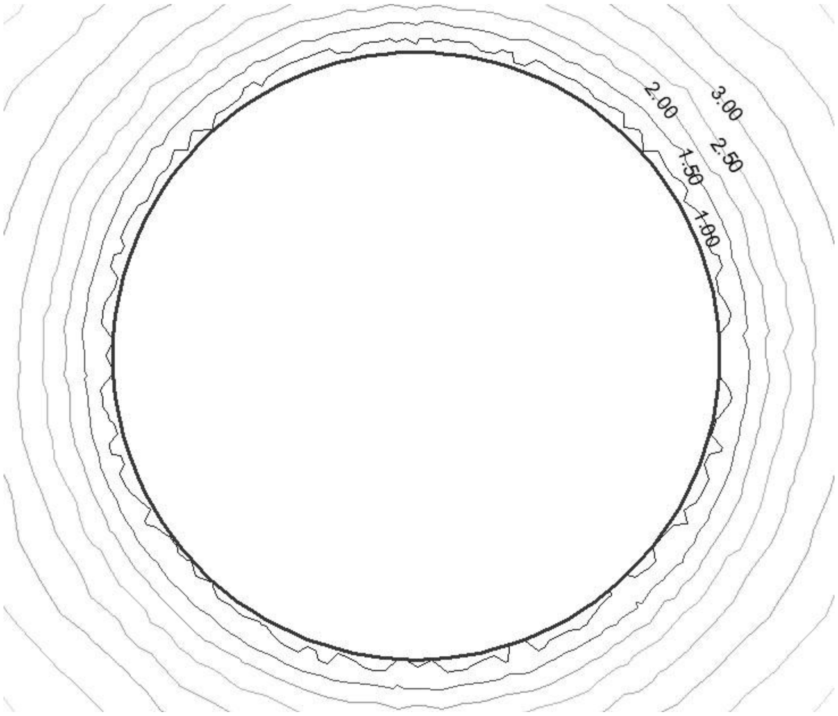

Figure 4. Minimum principal stresses

Three models were created with different sprayed concrete thicknesses (5 cm, 10 cm, 15 cm), while all other model parameters remained the same. Figures 3 and 4 show the distribution of maximum and minimum principal stresses. After the sprayed concrete lining is installed, the remaining load is applied. Figures 5 show the distribution of maximum and minimum principal stresses in the concrete lining for the case when 15 cm of sprayed concrete is used. Naturally, only the second part of the load acts on the concrete lining.

From the figure, it is clear that: The highest values of maximum principal stresses (5.5 MPa) and the lowest values of minimum principal stresses (0.08 MPa) occur on the outer surface of the concrete lining. The lowest values of maximum principal stresses (5.2 MPa) and the highest values of minimum principal stresses (0.32 MPa) occur near the rock.

Figure 5. Maximum and minimum principal stresses in the concrete lining

Therefore, the tensile stress values ($st = 0.1$) will be:

$$\sigma_t = st \cdot \sigma_1 - \sigma_3$$

On the outer side of the concrete lining:

$$\sigma_t = 0.1 \cdot 5.5 - 0.08 = 0.47 MPa$$

On the inner side of the concrete lining (adjacent to the rock):

$$\sigma_t = 0.1 \cdot 5.2 - 0.32 = 0.2 MPa$$

It is obvious that the distribution of stress is such that the greatest tensile stress will occur at the outer boundary surface of the concrete lining. If stress exceeds the limit, fracture will first appear on the surface of the concrete lining.

The maximum tensile stress near the outer surface of the concrete lining will have the same value regardless of whether the concrete is 10 cm or 15 cm thick (or any other thickness). Therefore, it is logical to install the minimum technologically acceptable thickness of sprayed concrete.

If the stress in the concrete lining is monitored actively, it is possible—before its elastic potential is exhausted—to apply a new "minimal" layer of sprayed concrete with adequate tensile strength in the direction of minimum principal stresses. This resolves the stability issue of underground openings, and it can be repeated multiple times. This is especially important for underground openings in the excavation zone.