ROCK FAILURE

A key issue in the analysis of stability and dimensioning of underground structures is: How and under what conditions does rock failure occur; What conditions must be met for failure to happen, i.e., what is the failure criterion. When this is known, it becomes possible to design a structure so that failure does not occur, including the dimensioning of the support structure. Failure will be explained through a simple and widely known experiment of uniaxial compressive loading. The loaded specimen deforms in both axial and radial directions it shortens in the direction of the load (σ_0) and expands perpendicular to it (radially). At a certain moment, the specimen fails, and the broken sample appears as shown in Figure 1. If the specimen has no predisposed planes of weakness, generally vertical tensile cracks are formed.

Figure 1. Appearance of a failed specimen

Tensile cracks in the compressed sample occur as a result of repacking of rock particles (Figure 2). The compressed particle "A" is pressed between particles "B" and "C," displacing them. While doing so, particle "A" slides along the contact surfaces with particles "B" and "C." As a result, the specimen is subjected to compressive stress axially, and tensile stress radially.

If the ratio of axial to radial dilatation is Poisson's ratio and if the modulus of elasticity is the same in compression and tension, then the same relationship holds for stresses. Thus, at the moment of failure, the radial compressive force pushing particles sideways is $(\nu \cdot \sigma_0)$. This force is resisted by cohesion, i.e., tensile strength (σ_t), and friction $(\sigma_t tg\varphi)$.

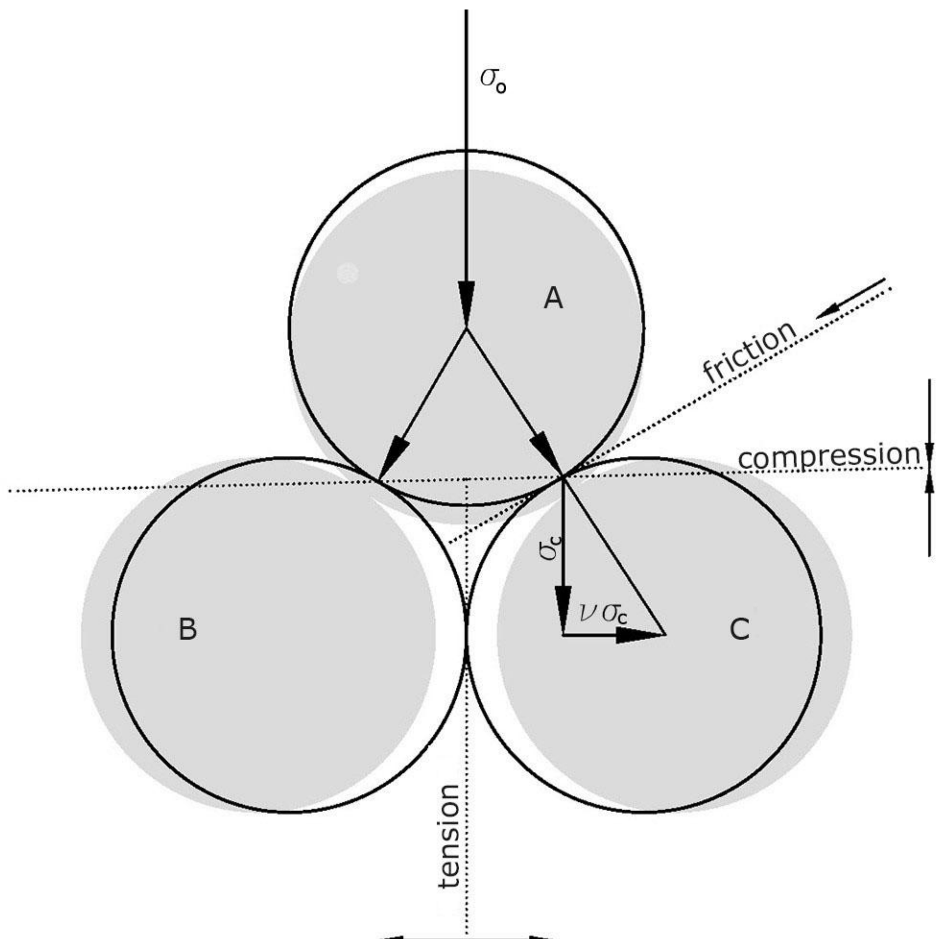

Figure 2. Mechanism of vertical tensile crack formation in a compressed specimen

Hence:

$$\nu\sigma_0 = \sigma_t + \sigma_t\, tg\varphi \text{ i.e.,}$$

$$\sigma_0 = \frac{\sigma_t}{\nu}(1 + tg\varphi) \text{ or:}$$

$$\sigma_t = \frac{\nu\sigma_0}{1 + tg\varphi}$$

This formula applies to the uniaxial compressive test and to rock mass along the boundary of underground spaces. In general:

$$\sigma_1 = \frac{\sigma_t + \sigma_3}{\nu}(1 + tg\varphi)$$

where σ_1 and σ_3 are the maximum and minimum principal stresses, respectively.

Stress and deformation curve

During the uniaxial compression test, the specimen's deformation is measured and the deformation curve is plotted often mistakenly called the stress-strain curve. This mistake comes from the incorrect assumption that the load applied by the piston to the specimen is numerically equal to the internal compressive stress.

A typical deformation curve from the uniaxial compression test (Figure 3) can be divided into three zones: Zone 1 is characterized by a linear relationship between load and deformation only elastic deformation occurs. The forces that cause deformation are smaller than the internal frictional resistance $(\sigma_t tg\varphi)$. Therefore, deformation is purely elastic, and the initial deformation modulus equals the modulus of elasticity. Then the curve becomes steeper due to the activation of internal friction as particles shift differently in contact. In this Zone 2, the deformation modulus is higher than the modulus of elasticity, but the relationship remains linear. Zone 3 begins when the curve bends i.e., the increase in deformation becomes greater than the increase in load. This happens when contact surfaces heat up from friction and the internal friction angle decreases. The total deformation work during loading is partially converted into potential energy of elastic deformation and partially into heat produced by friction, i.e., into entropy.

Lateral deformation is also measured during the uniaxial compression test to calculate Poisson’s ratio. In technical reports, the complete deformation curve is often presented (Figure 4), including the lateral deformation as a function of axial load.

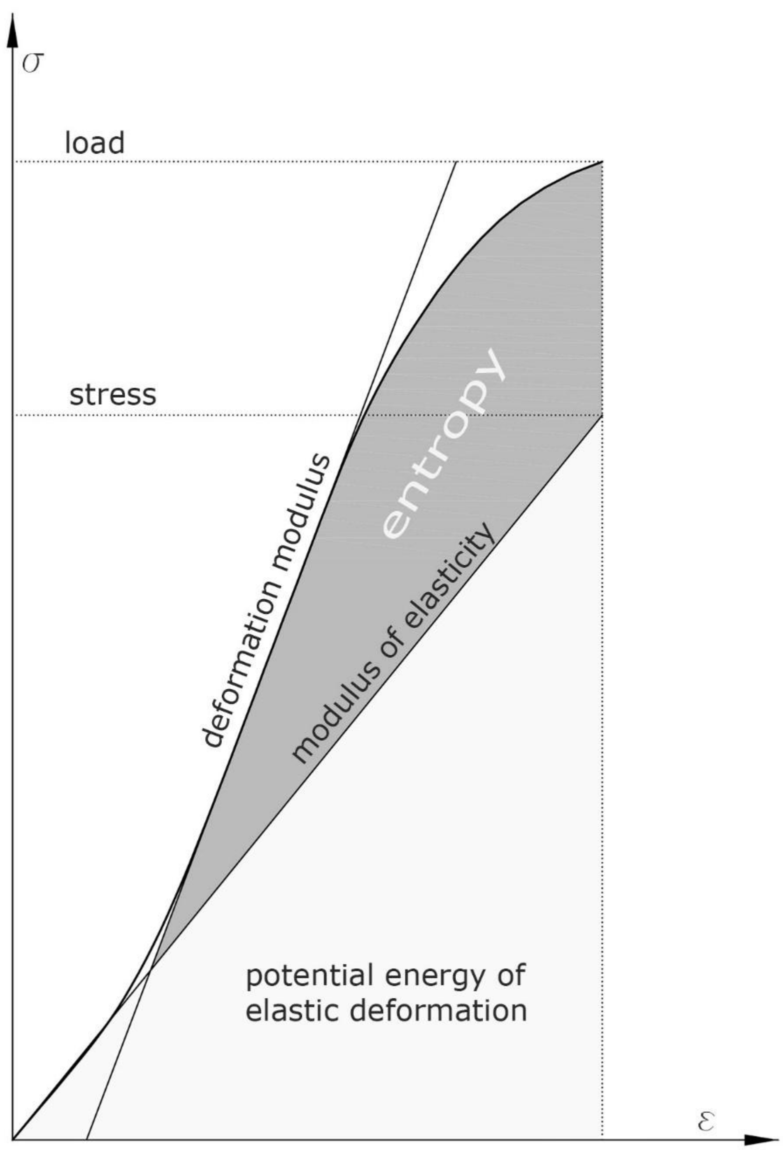

Figure 3. Deformation curve

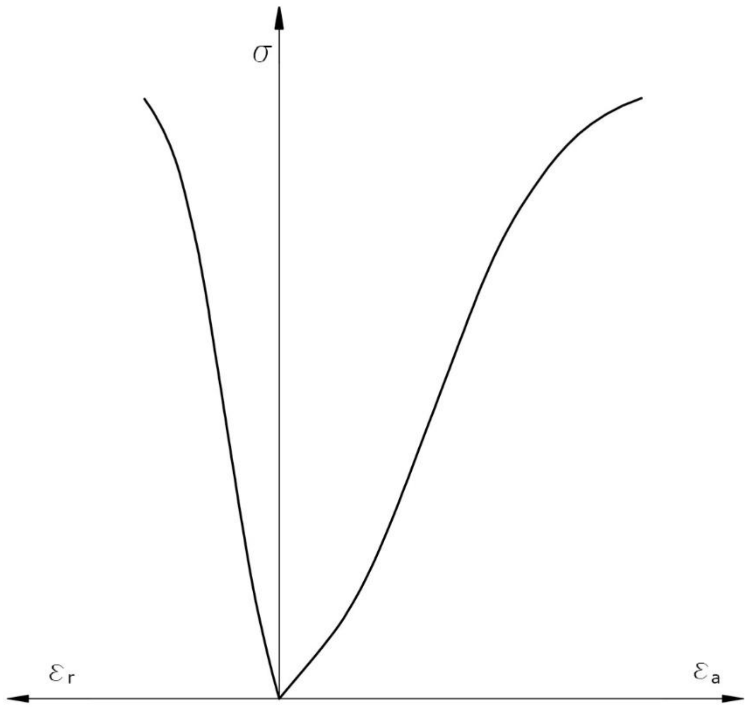

Figure 4. Complete deformation curve

This lateral curve should be plotted in the third quadrant, as shown in Figure 5, and constructed as follows: if the modulus of elasticity and deformation modulus are the same in both tension and compression, then for each deformation modulus and corresponding radial dilatation, the lateral load causing tension can be calculated.

With those values, the deformation curve of lateral dilatation as a function of lateral load causing tension can be drawn. In this way, the complete deformation curve is obtained.

The total deformation work in tension consists of the tensile stress or potential energy of elastic tension deformation and the entropy or deformation work of friction converted into heat.

Thus, based on a single uniaxial compressive test measuring axial and radial deformation, it is possible to:

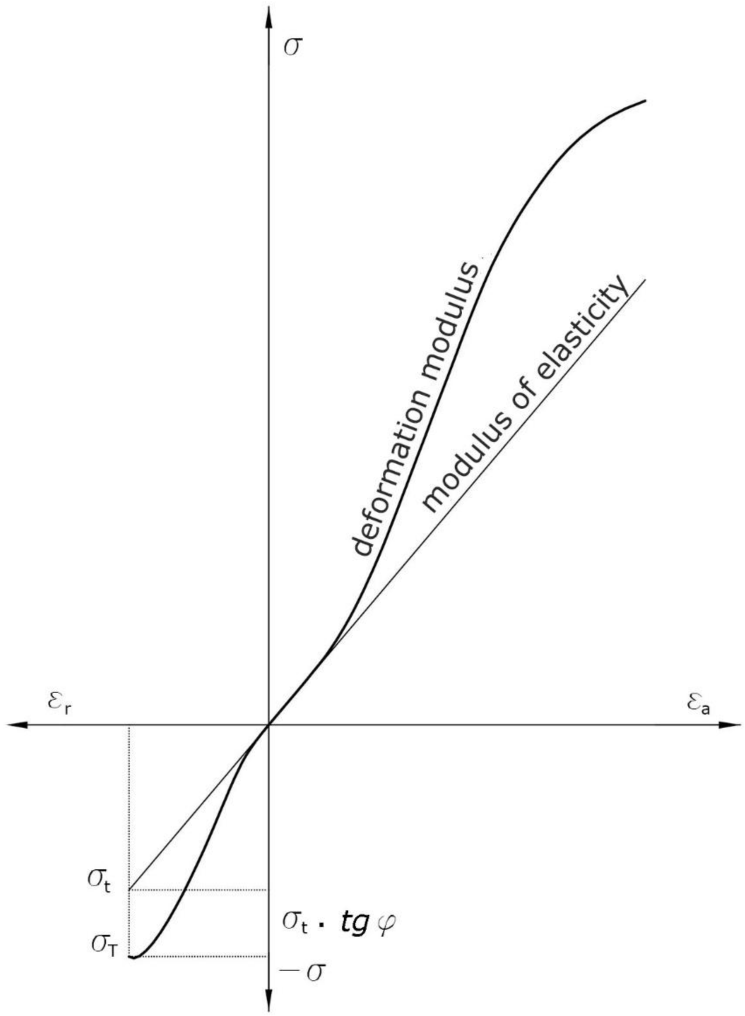

Figure 5. Pressure–tension deformation curve

- Draw the pressure–tension deformation curve to determine the deformation modulus (E_d)
- Determine the modulus of elasticity (E)
- Calculate Poisson's ratio (ν)
- Determine the lateral load causing tension (σ_T)
- Determine tensile strength (σ_t)
- Calculate the internal friction angle: $tg\varphi = \frac{\sigma_T}{\sigma_t} - 1$

A single simple and inexpensive test provides all the strength and deformability parameters needed for stability analysis.