

Structural Resistance

Rock in the Earth's crust, in its natural environment before any engineering activity, is characterized by:

- A discrete structure. It is composed of particles of rock material held together by cohesive forces. When an external cause leads to the separation of particles, tensile stress is induced between them, defined by Hooke's law. When the distance between particles due to tension reaches a critical value, the cohesive forces between them vanish, and it becomes impossible to induce tensile stress at that location. The structure of the rock changes.
- The natural state of the rock in the Earth's crust is characterized by stress. This stress is conditioned by the origin and structure of the Earth, i.e., by gravity as a fundamental force in nature and by inertial forces resulting from changes in momentum in particular parts of the Earth's crust. These are mainly due to gravitational interaction with the Moon, but also with other planets. The stress in the rock is potential energy, equivalent to its elastic deformation.

When part of the rock is removed from the natural structure of the rock mass, the particles around the resulting cavity move toward the empty space because they have lost the support of the removed particles. Deformation work is performed, equivalent to the potential energy of the elastically deformed rock.

Resistance to the deformation of the rock, i.e., to the displacement of rock particles, is provided by cohesive forces, frictional resistance between differently moving particles, and the resistance of the constructed support structure.

The resistance of the structure is illustrated in Figure 1, showing the deformation state of an underground opening with a rectangular cross-section. If we observe only the roof of the opening, angular zones stand out—where deformation is influenced by the shape of the opening—and a central zone with a plane strain state. A detail of the corner, with small circles symbolizing particles in a 2D view, is shown in Figure 2. Particles forming the roof of the opening, which have lost support due to the removal of particles formerly occupying the now empty space, begin moving toward that empty space.

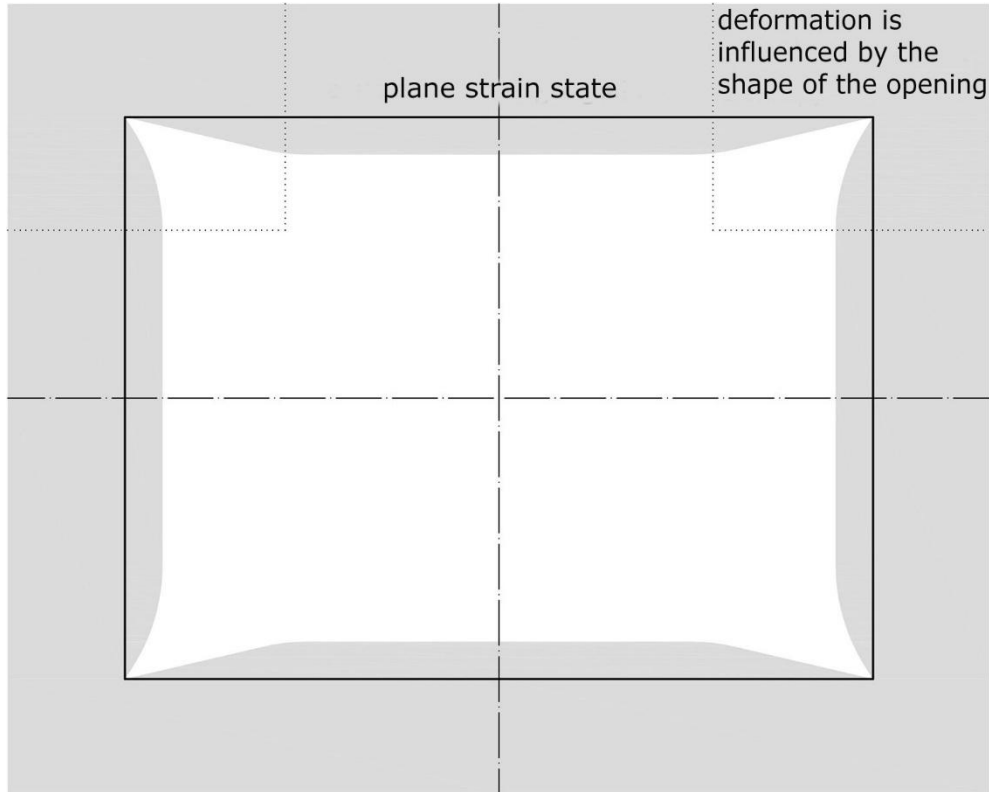


Figure 1. Deformation state of the underground opening

The first particle in the corner, forming the roof, is in lateral contact with a stationary particle. As a result, its movement is resisted by friction between the two particles, so its movement is proportionally reduced. The next particle in the sequence will have a longer displacement, proportional to the friction between the two neighboring particles. After a certain distance, when the effect of lateral friction is exhausted, all particles have the same displacement, appropriate to the stress and the modulus of elasticity. A line is drawn through the centers of all displaced particles with reduced displacement. The angle between this line and a line drawn through the centers of the same particles in their previous position is, in fact, the angle of internal friction (φ).

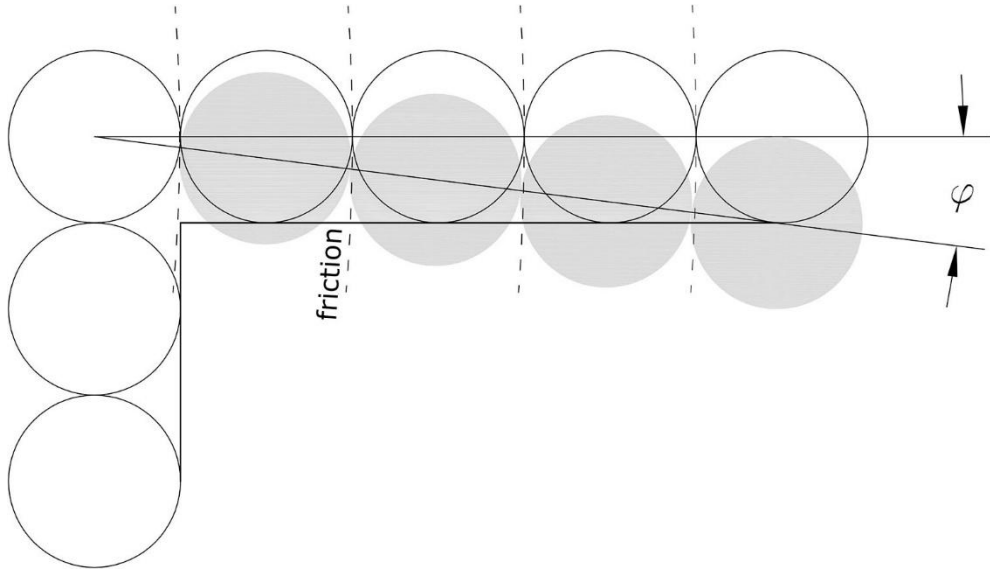


Figure 2. Influence of structural resistance on deformation

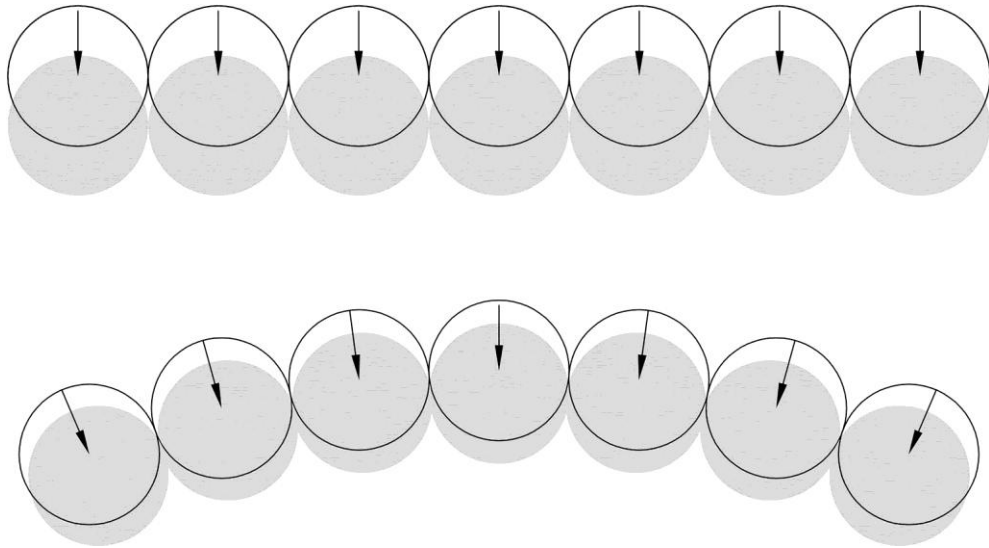


Figure 3. Influence of structural resistance on deformation

When the roof of the opening is observed without lateral influence, i.e., when the entire roof is in a plane strain (or stress) state (Figure 3), all particles move simultaneously at the same speed and there is no frictional resistance between adjacent particles. When the same roof is constructed in the form of a circular arch, all particles that have lost support move toward the empty space in the direction of the center of the circular arc.

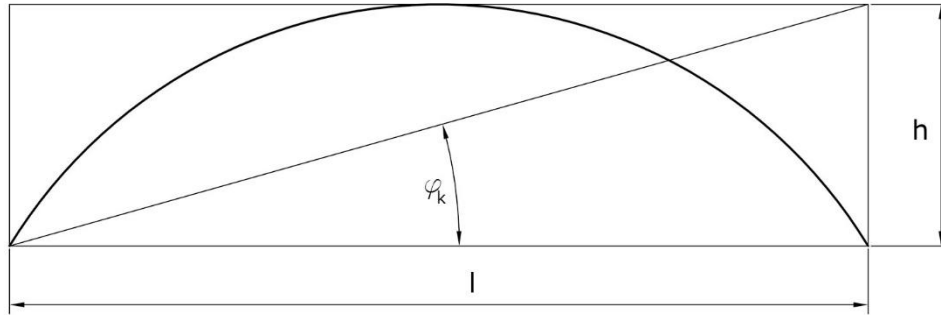


Figure 4. Determining the structural friction angle

Their movement is additionally resisted by the fact that their trajectories intersect at the center of the circular arc. This additional resistance is the structural resistance and is expressed as an additional friction angle. Hence, the effective friction angle ($\bar{\varphi}$) consists of the material friction angle (φ_m) and the structural friction angle (φ_k), i.e.:

$$\bar{\varphi} = \varphi_m + \varphi_k$$

The structural friction angle is determined geometrically, as shown in Figure 4. The figure shows the roof part of the underground opening and the structural friction angle which quantifies the resistance of the structure. In fact, it is simpler to calculate the tangent of that angle directly and add it to the tangent of the material friction angle.