SINGLE TUNNEL JOINTS

A zone of compressive stress concentration at the wall of a tunnel may increase or decrease the stability of any joints present depending on the joint orientation and joint properties. Joint orientation is concerning the directions parallel and perpendicular to the tunnel wall. The perpendicular or normal to a tunnel wall coincides with a principal stress direction. A common assumption is that the long axis of a tunnel is also a principal direction, so a third principal stress direction is tangential to the tunnel wall as seen in the cross-section.

Generally, there is a range of unstable orientations that depends on joint cohesion cj, friction angle φj, and tunnel stress state. Cohesive joints that are nearly perpendicular or nearly parallel to a tunnel wall are likely to be safe concerning slip-in shear. However, parallel joints may form slabs through separation under tension. Whether joint slip occurs requires a three-dimensional calculation of normal and shear stresses acting on joints that intersect tunnel walls. The normal joint stress is needed to compute joint strength, while the shear stress is needed to compute a joint safety factor. If the normal joint stress is tension, then one may reasonably suppose separation is likely. If one assumes Mohr-Coulomb joint strength, then the joint safety factor concerning slip-in shear is

$$\mathrm{FS_j} = \frac{\tau(\mathrm{strength})}{\tau(\mathrm{stress})} = \frac{\sigma'_{\mathrm{j}}\tan(\phi_{\mathrm{j}}) + c_{\mathrm{j}}}{\tau_{\mathrm{j}}}$$

where the subscript j refers to “joint” and the prime denotes effective normal stress. The direction of joint slip is reasonably supposed to occur in the direction of maximum joint shear stress. Because the considered joint intersects the tunnel wall, any joint slip would result in an offset at the tunnel wall. In the common case of cohesionless joints, joint slip may occur when

$$\phi_{\mathrm{j}} < \beta = \tan^{-1}\left(\frac{\tau_{\mathrm{j}}}{\sigma_{\mathrm{j}}}\right)$$

that has the simple geometric interpretation of a “friction cone” shown in Figure 1. Even in the simplified case of cohesionless joints and the coincidence of the long tunnel axis with a principal stress direction, the calculation of joint normal and shear stresses is lengthy. It requires knowledge of the principal stress acting parallel to the tunnel axis as well as wall stress concentration factor and pre-excavation stresses.

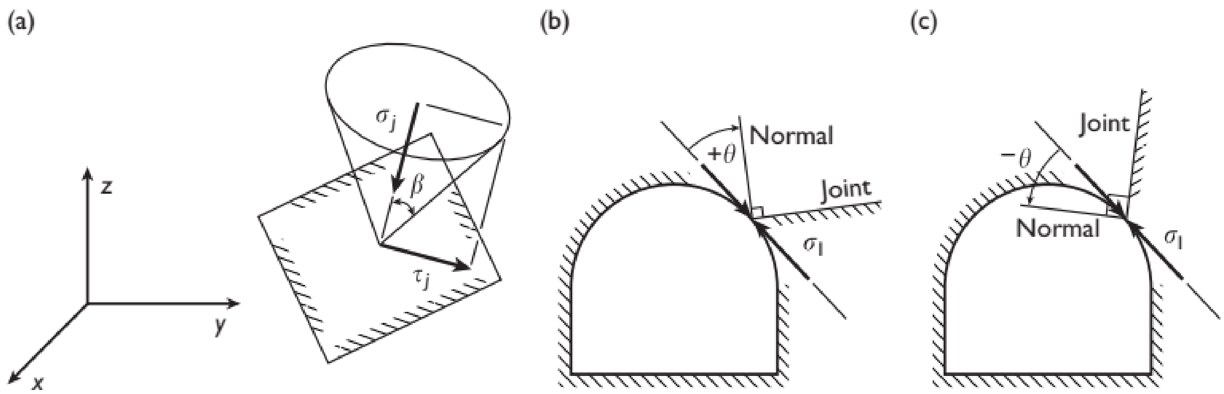

Figure 1 Joint plane friction cone and sign convention for orientation angle at tunnel: (a) joint plane friction cone, (b) positive θ, and (c) negative θ.

However, when the joint strike is also parallel to the long axis of a tunnel, one may determine algebraically a range of unstable joint normal orientations. Given joint and rock shear strength according to Mohr-Coulomb criteria, as shown in Figure 2, joint slip is indicated by computed joint safety factors less than one, that is, if

$$\mathrm{FS_j} = \frac{[\sigma_\mathrm{m} + \tau_\mathrm{m}\cos(2\theta)]\tan(\phi_\mathrm{j}) + c_\mathrm{j}}{\tau_\mathrm{m}\sin(2\theta)} < 1$$

then joint slip is possible. The inequality on the right may be solved for the range of the angle θ that defines unstable joint orientations. Thus, if

$$\sin(2\theta - \phi_\mathrm{j}) > \sin(\phi_\mathrm{j}) + \frac{2c_\mathrm{j}\cos(\phi_\mathrm{j})}{\sigma_1}$$

then joint slip is possible. Alternatively, if

$$c_\mathrm{j} > \frac{\sigma_1(1 - \sin(\phi_\mathrm{j}))}{2\cos(\phi_\mathrm{j})}$$

then joint slip is not possible. In this analysis, positive angles in the $\sigma - \tau$ plane are counterclockwise; corresponding angles in the physical plane of a tunnel are opposite, clockwise. This reversal allows one to use the upper half of the $\sigma - \tau$ plane for analysis using the usual mathematical convention of positive angles measured in a counterclockwise direction. Inspection of Figure 2 shows that the range of unstable joint orientations is limited by solutions to

$$\sin[(2\theta - \phi_j)] > \sin(\phi_j) + \frac{2c_j\cos(\phi_j)}{\sigma_1}$$

$$\sin[\pi - (2\theta - \phi_j)] < \sin(\phi_j) + \frac{2c_j\cos(\phi_j)}{\sigma_1}$$

In either case, the tunnel wall compression is given by

$$\sigma_1 = KS_1$$

where K and S_1 are the stress concentration factor and major principal stress before excavation, respectively. Thus, the limiting range of unstable joint orientations is given by

$$2\theta_1 < 2\theta < 2\theta_2$$

$$2\theta_1 = \phi_j + \sin^{-1}\left[\sin(\phi_j) + \frac{2c_j\cos(\phi_j)}{\sigma_1}\right]$$

$$2\theta_2 = \pi + \phi_j - \sin^{-1}\left[\sin(\phi_j) + \frac{2c_j\cos(\phi_j)}{\sigma_1}\right]$$

The range defined by solutions to these inequalities is ultimately limited by the unconfined compressive strength ($Co = \sigma_1$) of intact rock between joints.

When the considered joint lacks cohesion, the range of angles between the tangent to the tunnel wall and the normal to the joint is

$$\theta_1 < \phi_j < \pi = \theta_2$$

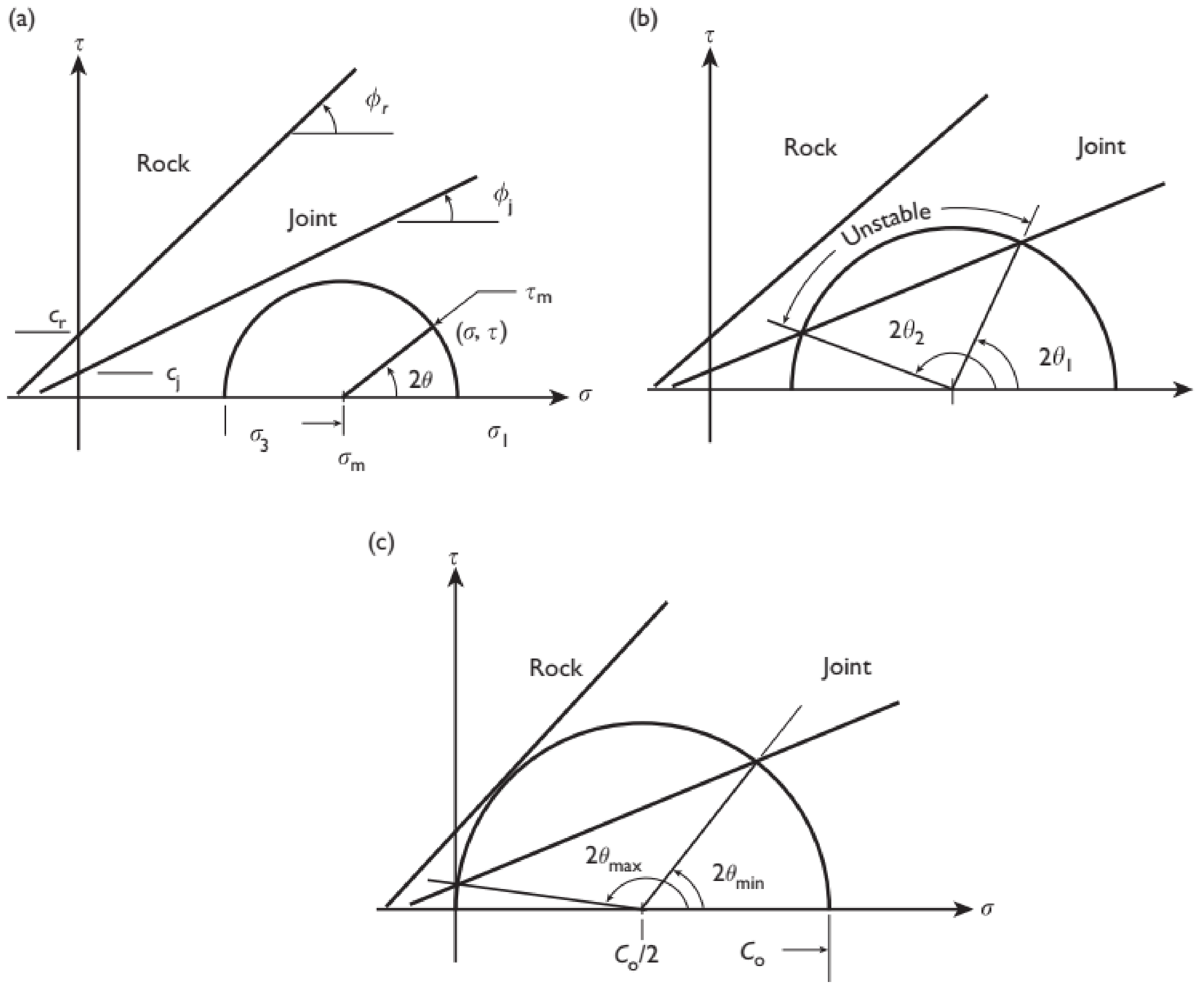

Figure 2 Mohr circle construction for a range of joint failure orientations when joints strike parallel: (a) no failure, (b) joint failures $2\theta_1 < 2\theta < 2\theta_2$, and (c) rock and joint failure under uniaxial compression.

which simply states that frictional sliding occurs when the "slope" is greater than the friction angle. A similar analysis may be done in the lower half of the σ –τ plane where shear stresses are negative. A confusion of algebraic signs suggests one handles the situation by inspection rather than analysis. Indeed, a mirror image of the graphics in Figure 2 shows analogous results with negative signs for angles θ, reflective of joint orientation symmetry about the direction of σ1 tangential to the tunnel wall.

Example 1 Suppose joint and intact rock properties are determined by laboratory tests on samples acquired at a tunnel site and are: cr = 1,500 psi, cj = 15 psi, ϕr = 45°, ϕj = 25°. Analysis indicates that stress concentration in the arch of the tunnel back peaks at 2.87 over the shoulder of the tunnel where the wall slope is inclined 75° to the horizontal. Stress measurements indicate pre-excavation vertical stress of 600 psi and horizontal stress of 150 psi. Determine if joint slip is possible and, if so, the range of joint normal that allows slip.

Solution: The tunnel wall stress is

$\sigma 1 = (2.87)\ (600) = 1,772$ psi

and therefore

$\sigma 1\ (1 - \sin(\phi j)/2 \cos(\phi j) = (1,772)\ [1 - \sin(25)]\ /\ [2 \cos(25)] = 564$ psi

which is greater than $cj = 15$ psi,

so joint slip is possible.

The range of normal may determine from

$$2\theta_1 = 25 + \sin^{-1}\left[\sin(25) + \frac{2(15)\cos(25)}{1{,}772}\right] = 51.0°$$

$$2\theta_2 = 180 + 25 + \sin^{-1}\left[\sin(25) + \frac{2(15)\cos(25)}{1{,}772}\right] = 231.0°$$

The range of normal is, therefore (25.5°, 115.5°) measured from σ1 in either a clockwise or counter-clockwise direction. The joint planes proper prone to slip range between 15.5 and 74.5° on either side of σ1.

Example 2 Consider an arched back tunnel with a height of 6 m and a width of 4 m at a depth of 1,000 m where before excavation the vertical stress is 20 MPa and horizontal stress is 5 MPa as seen in the cross-section. A fault dipping 60° intersects the tunnel 3 m above the floor on the right-hand side (looking at the face). The fault friction angle is 32° and fault cohesion is 1 kPa. Determine whether fault slip is possible and if so, what improvement in cohesion would be required, say by grouting, to give a fault slip safety factor of 1.1.

Solution: The tunnel height-to-width ratio is 3/2, and the pre-excavation principal stress ratio is 1/4th by the given conditions. The intersection of the fault with the tunnel wall is in the rib. According to the trend lines in Figure 3, the rib stress concentration is

$$K = (1)[(-0.132(3/2)) + 2.676] + (1/4)[(-0.128(3/2)) - 0.831] = 1.46$$

The rib stress σ1 = 1.46 (20) = 29.2 MPa which acts vertically at the rib-side. Slip is possible if

$$\frac{\sigma_1[1 - \sin(\phi)]}{2\cos(\phi)} > c_\mathrm{j}$$

$$\frac{29.2[1 - \sin(32)]}{2\cos(32)} = 9.09 > 0.1 = \mathrm{MPa}$$

The inequality is satisfied and slipping is possible. To prevent slip by increasing cohesion to obtain a safety factor of 1.1 requires

$$\begin{aligned}
\mathrm{FS}(\mathrm{fault}) &= \frac{[\sigma_1 + \sigma_1\cos(2\theta)]\tan(\phi) + 2c}{\sigma_1\sin(2\theta)} = 1.1 \\
&= \frac{[1 + \cos(2\theta)]\tan(\phi) + 2c/\sigma_1}{\sin(2\theta)} = 1.1 \\
&= \frac{[1 + \cos(180)]\tan(32) + 2c/29.2}{\sin(32)} = 1.1
\end{aligned}$$

$$\therefore\ c = 8.51\,\mathrm{MPa}$$

When multiple joint sets are present, blocks of rock formed by joint intersections may be liberated during tunnel excavation. The fall of one block may allow other blocks to fall in turn. The threat to tunnel safety in this situation is highly dependent on the presence of a “key block” in allusion to stone arches and a central keystone that is essential to arch stability.

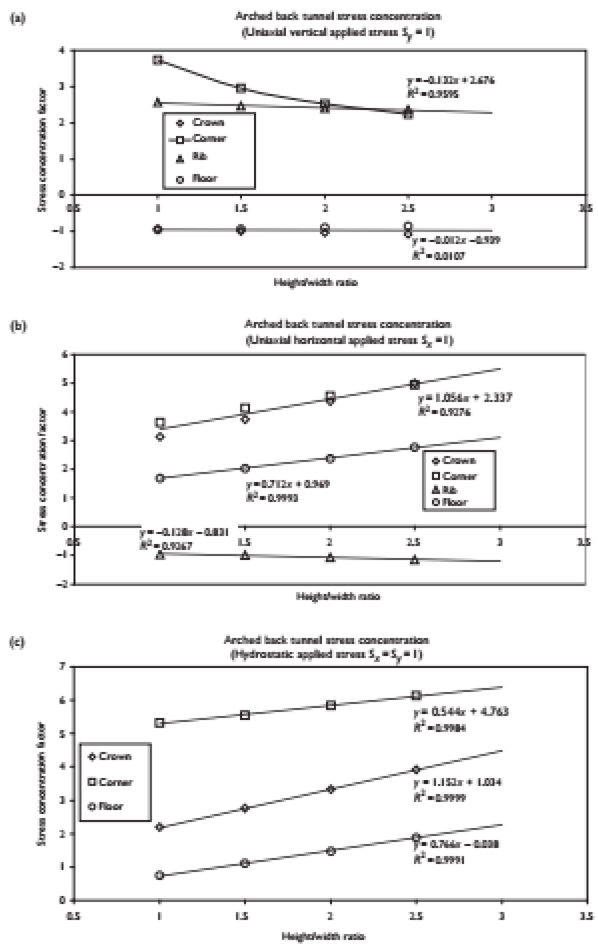

Figure 3 Stress concentration trends at key points of single arched back tunnel sections (a) vertical load,

(b) horizontal load and

(c) hydrostatic load.