Rock-Support Interaction analysis for tunnels in weak rock masses

Introduction

Tunnelling in weak rock presents some special challenges to the geotechnical engineer since misjudgements in the design of support systems can lead to very costly failures. In order to understand the issues involved in the process of designing support for this type of tunnel it is necessary to examine some simple basic concepts of how a rock mass surrounding a tunnel deforms and how the support systems act to control this deformation. This Rock-Support Interaction or Convergence-Confinement analysis is limited to circular tunnels in an in-situ stress field in which all three principal stresses are equal and where the rock mass exhibits elastic-perfectly plastic shear failure. It should not be used for the detailed design of tunnels in more complex rock masses and in-situ stress fields. More comprehensive analyses are available for these situations (Hoek et al, 2008).

Deformation around an advancing tunnel

Figure 1 shows the results of a three-dimensional finite element analysis of the deformation and failure of the rock mass surrounding a circular tunnel advancing through a weak rock mass subjected to equal stresses in all directions. The plot shows displacement vectors in the rock mass, the shape of the deformed tunnel profile and the shape of the plastic zone surrounding the tunnel. Figure 2 gives a graphical summary of the most important features of this analysis.

Elastic deformation of the rock mass starts about two diameters ahead of the advancing face and reaches its maximum value at about two diameters behind the face. At the face position about one third of the total radial closure of the tunnel has already occurred and the tunnel face deforms inwards as illustrated in Figures 1 and 2. Whether or not these deformations induce stability problems in the tunnel depends upon the ratio of rock mass strength to the in situ stress level, as will be demonstrated in the following pages.

Note that it is assumed that the deformation process described occurs immediately upon excavation of the face. This is a reasonable approximation for most tunnels in rock. The effects of time dependent deformations upon the performance of the tunnel and the design of the support system will be not be discussed in this chapter.

Tunnel deformation analysis

In order to explore the concepts of rock support interaction in a form which can readily be understood, a very simple analytical model based on the Mohr-Coulomb failure criterion will be utilised. This model involves a circular tunnel subjected to a hydrostatic stress field in which the horizontal and vertical stresses are equal.

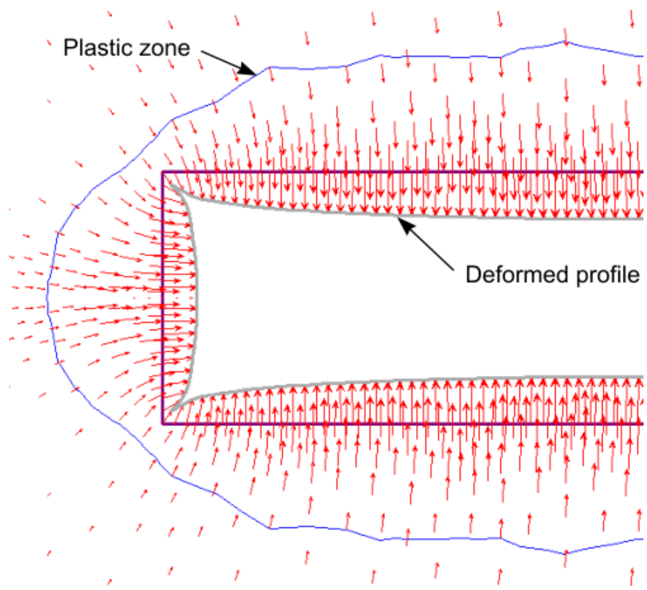


Figure 1: Vertical section through an axi-symmetric three-dimensional finite element model of the failure and deformation of the rock mass surrounding the face of an advancing circular tunnel. The plot shows displacement vectors as well as the shape of the deformed tunnel profile.

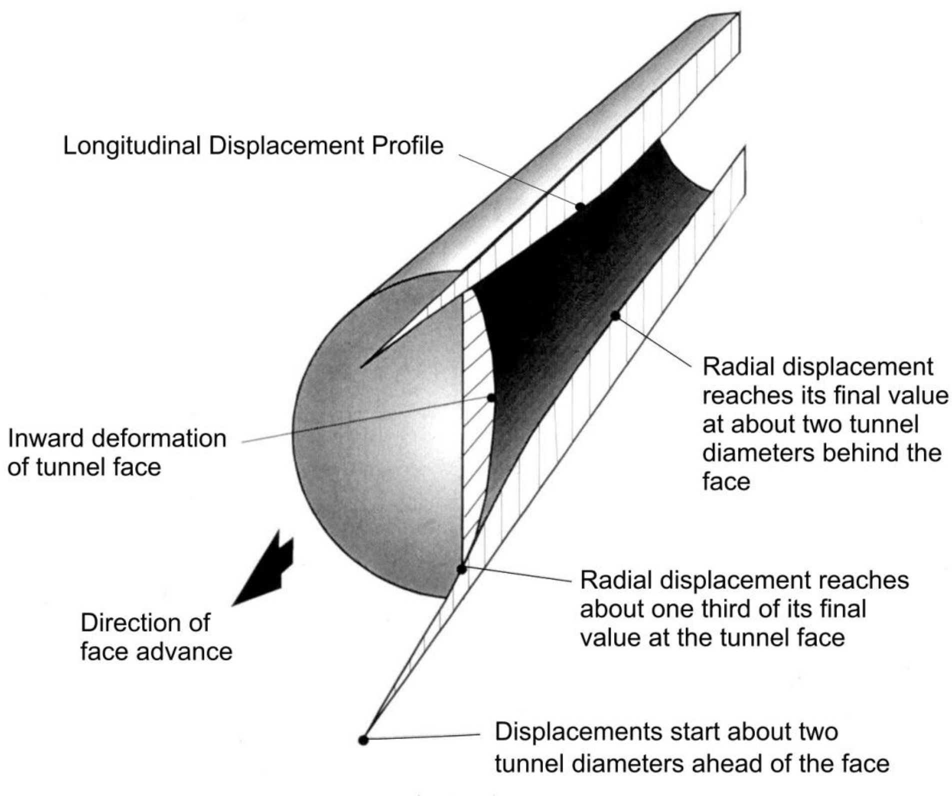


Figure 2: Pattern of elastic deformation in the rock mass surrounding an advancing tunnel.

In this analysis it is assumed that the surrounding homogeneous weak rock mass behaves as an elastic-perfectly plastic material in which failure involving slip along closely spaced intersecting discontinuities is assumed to occur with zero plastic volume change (Duncan Fama, 1993).

Definition of failure criterion

It is assumed that the onset of plastic failure, for different values of the effective confining stress $\sigma_3^{'}$, is defined by the Mohr-Coulomb criterion and expressed as:

$$\sigma_1^{'} = \sigma_{cm} + k\sigma_3^{'} \tag{1}$$

The uniaxial compressive strength of the rock mass σ_{cm} is defined by:

$$\sigma_{cm} = \frac{2c^{'} \cos\phi^{'}}{(1-\sin\phi^{'})} \tag{2}$$

and the slope k of the $\sigma_1^{'}$ versus $\sigma_3^{'}$ plot as:

$$k = \frac{(1+\sin\phi^{'})}{(1-\sin\phi^{'})} \tag{3}$$

where $\sigma_1^{'}$ is the axial stress at which failure occurs
$\sigma_3^{'}$ is the confining stress
$c^{'}$ is the cohesive strength and
$\phi^{'}$ is the angle of friction of the rock mass

Analysis of tunnel behaviour

Assume that a circular tunnel of radius r_o is subjected to hydrostatic stresses p_o and a uniform internal support pressure p_i as illustrated in Figure 3. Failure of the rock mass surrounding the tunnel occurs when the internal pressure p_i is less than a critical support pressure p_{cr}, which is defined by:

$$p_{cr} = \frac{2p_o - \sigma_{cm}}{1+k} \tag{4}$$

If the internal support pressure p_i is greater than the critical support pressure p_{cr}, no failure occurs, the behaviour of the rock mass surrounding the tunnel is elastic and the inward radial elastic displacement u_{ie} of the tunnel wall is given by:

$$u_{ie} = \frac{r_o(1+\nu)}{E_m}(p_o - p_i) \tag{5}$$

where E_m is the Young's modulus or deformation modulus and
ν is the Poisson's ratio of the rock.

When the internal support pressure p_i is less than the critical support pressure p_{cr}, failure occurs and the radius r_p of the plastic zone around the tunnel is given by:

$$r_p = r_o \left[\frac{2(p_o(k-1)+\sigma_{cm})}{(1+k)((k-1)p_i+\sigma_{cm})} \right]^{\frac{1}{(k-1)}} \tag{6}$$

For plastic failure, the inward radial displacement u_{ip} of the walls of the tunnel is:

$$u_{ip} = \frac{r_o(1+\nu)}{E}\left[2(1-\nu)(p_o - p_{cr})\left(\frac{r_p}{r_o}\right)^2 - (1-2\nu)(p_o - p_i) \right] \tag{7}$$

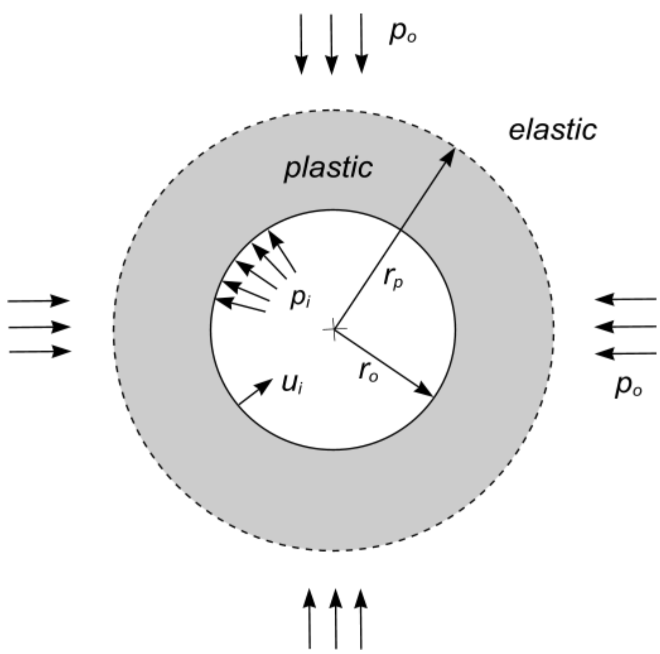
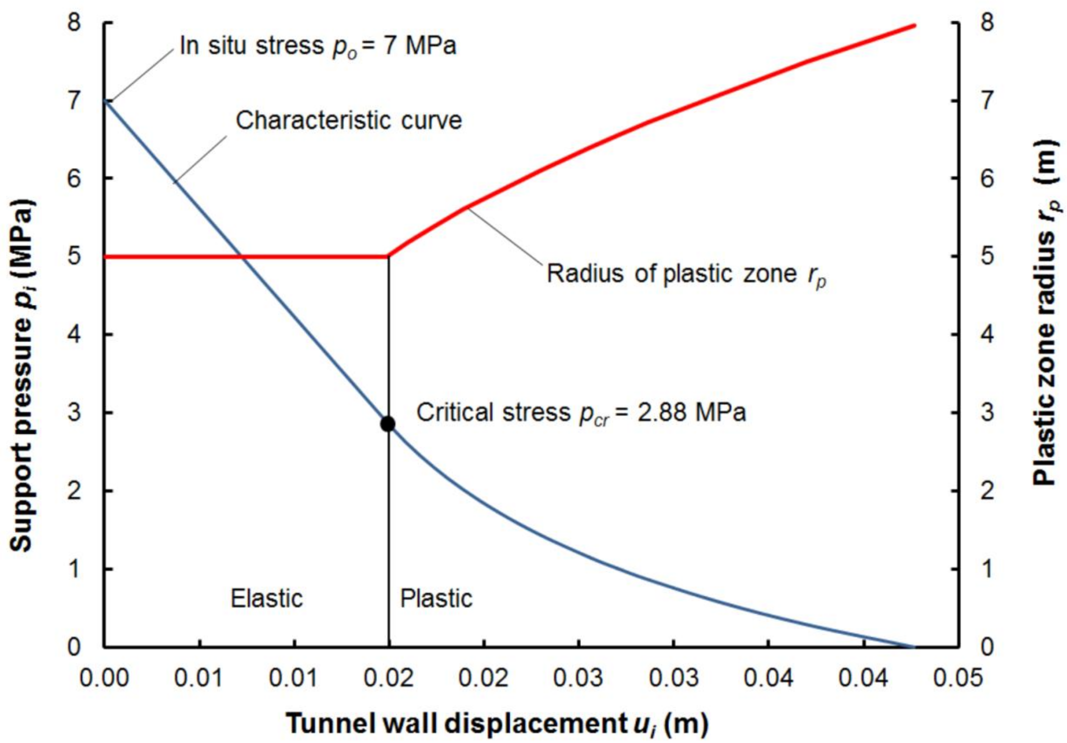


Figure 3: Plastic zone surrounding a circular tunnel.

Characteristic curve for a tunnel

Equations 4 to 7, presented above, define the relationship between internal support pressure p_i and the tunnel deformation u_i for an advancing circular tunnel in a hydrostatic stress field. A plot of u_i versus p_i is generally known as the *Characteristic Curve* for the tunnel and an example is given in Figure 4. This curve is based on the assumption that the rock at the tunnel face provides an initial support pressure equal to the in situ stress p_o. As the tunnel face advances and the face moves away from the section under consideration, the support pressure gradually decreases until it reaches zero at some distance behind the face. Also included in Figure 4 is the radius of the plastic zone r_p, calculated from equation 6.



Input:	Output:
Tunnel radius r_o = 5 m	Rock mass UCS σ_{cm} = 4.53 MPa
Friction angle ø = 23°	Rock mass constant k = 2.28
Cohesion c = 1.5 MPa	Critical pressure p_{cr} = 2.88 MPa
Modulus E = 1800 MPa	Max tunnel displacement = 0.0427 m
Poisson's ratio ν = 0.3	Max plastic zone radius = 7.96 m
In situ stress p_o = 7 MPa	Plastic zone/tunnel radius = 1.592

Figure 4: Characteristic curve for a tunnel excavated in weak rock.