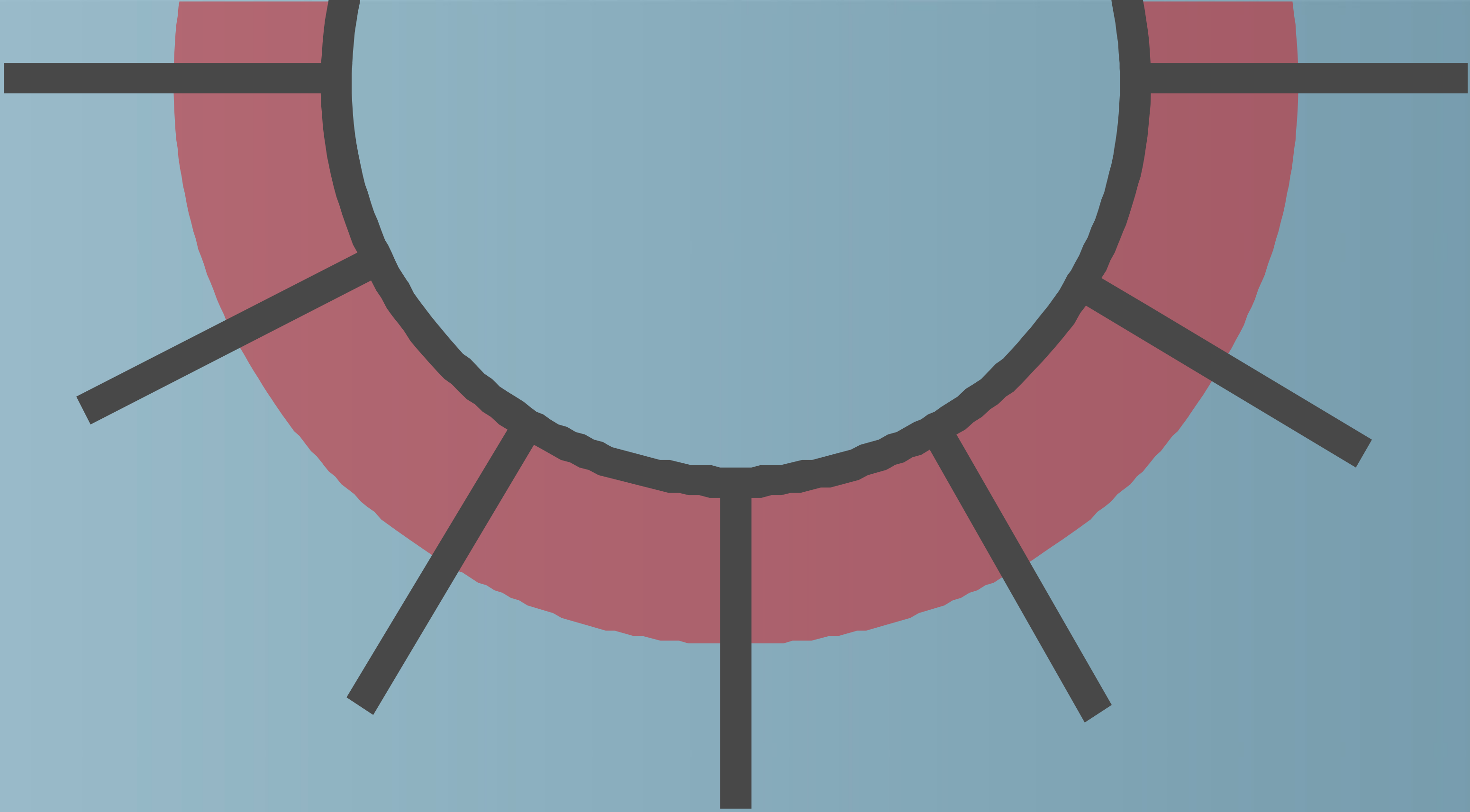


RocSupport

Introduction Manual

Topics Covered:

- Rock Support Interaction Solution Method
- Ground Reaction Curve
- Support Reaction
- Solution Methods
- Deterministic Analysis
- Probabilistic Analysis

rocscience

Introduction

RocSupport is a quick and simple to use program for estimating the deformation of circular tunnels in weak rock, and visualizing the tunnel interaction with various support systems.

The analysis method used in *RocSupport* is often referred to as “rock support interaction” or “convergence-confinement” analysis. This analysis method is based on the concept of a “ground reaction curve” or “characteristic line,” obtained from the analytical solution for a circular tunnel in an elasto-plastic rock mass under a hydrostatic stress field.

Applicability of Method

The main assumptions in the analysis method are as follows:

- tunnel is circular
- in-situ stress field is hydrostatic (i.e. equal stress in all directions)
- rock mass is isotropic and homogeneous. Failure is not controlled by major structural discontinuities.
- support response is elastic-perfectly plastic
- support is modeled as an equivalent uniform internal pressure around the entire circumference of the circular tunnel

This last assumption in particular (that support is uniform around the entire circumference of the tunnel), should be carefully considered by the user, when comparing actual tunnel behavior, and calculated results using *RocSupport*.

The assumption of uniform support pressure implies that:

- shotcrete and concrete linings are closed rings
- steel sets are complete circles
- mechanically anchored rockbolts are installed in a regular pattern which completely surrounds the tunnel.

Because this will not usually be the case, actual support capacities will be lower, and deformations larger, than those assumed in *RocSupport*.

The idealized model used for a *RocSupport* analysis is not intended to replace detailed final design and analysis requirements for tunnel support. In general, this will require numerical analysis (e.g. finite element), particularly for tunnels with large strain.

However, a great deal can be learned about the interaction of tunnels in weak rock, with various support systems, by carrying out parametric studies using *RocSupport*, in which different combinations of in-situ stress levels, rock mass strengths and support characteristics are evaluated.

Methods of Support Design

Although there are no clearly defined rules for tunnel support and lining design at the present time, three general methods have emerged over recent years. These can be described as:

1. Closed form solution methods that are based upon the calculation of the extent of “plastic” failure in the rock mass surrounding an advancing tunnel, and the support pressures required to control the extent of the plastic zone and the resulting tunnel deformation.
2. Numerical analysis of the progressive failure of the rock mass surrounding an advancing tunnel and of the interaction of temporary support and final lining with this failing rock mass.
3. Empirical methods based upon observations of tunnel deformation and the control of this deformation by the installation of various support measures.

RocSupport belongs to the first category of solution methods, i.e. “rock support interaction” or “convergence-confinement” methods.

A good example of a numerical analysis program which belongs to the second category, is *RS2*, a finite element stress analysis and support design program for underground excavations, also available from *Rocscience*.

Each of these methods has advantages and disadvantages, and the optimum solution for a given tunnel design, may involve a combination of different methods, at different stages of the design. For example, a preliminary analysis of temporary support requirements could be
carried out with *RocSupport*, and detailed final design, including plastic failure of the rock mass, and yielding support, can be carried out with *RS2*.

In spite of the limitations discussed above, rock support interaction analysis has many attractions, and when used in conjunction with numerical analyses, it can provide valuable insights into the mechanics of rock support, and reasonable guidelines for the design of this support.

Rock Support Interaction

A starting point for a discussion of the “rock support interaction” method, is to discuss the deformation which occurs in the vicinity of an advancing tunnel face, for an unsupported tunnel. This is illustrated in the following figure.

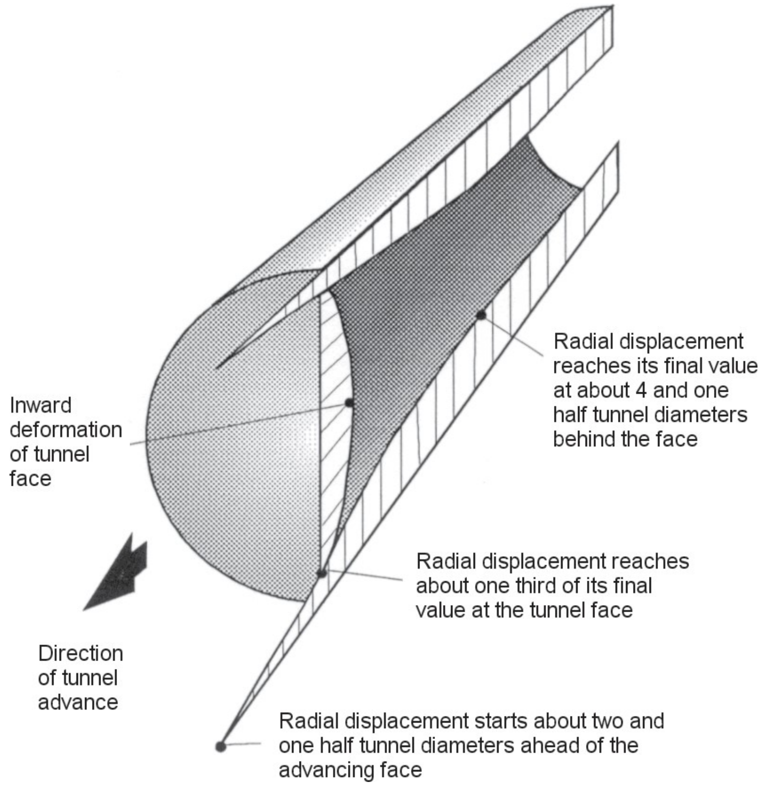


Figure 1-1: Radial displacements around an advancing tunnel face (not to scale). (Hoek, 1998).

Note that the radial displacement:

- begins a certain distance ahead of the tunnel face (about two and one-half tunnel diameters)
- reaches about one third of its final value AT the tunnel face
- reaches its maximum value at about four and one-half tunnel diameters behind the face

It is important to note that even for an unsupported tunnel, the tunnel face provides an "apparent support pressure." It is this apparent support pressure that provides the stability to give sufficient stand-up time for the actual support to be installed.

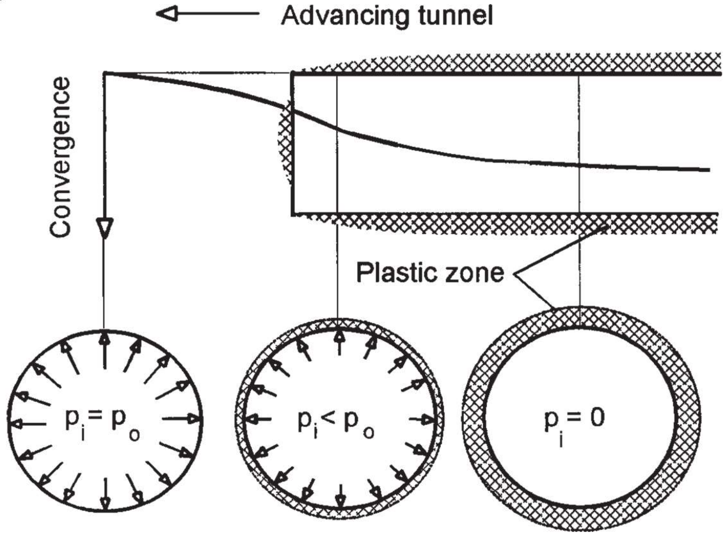


Figure 1-2: Support pressure p_i at different positions relative to the advancing tunnel face (not to scale). (Hoek, 1999a)

Observe that the apparent support pressure:

- is equal to the in-situ stress (i.e. $p_i = p_o$) at a certain distance (about two and one-half tunnel diameters) within the rock mass, ahead of the advancing face
- is equal to about one-quarter of the in-situ stress, at the tunnel face
- gradually reduces to zero at a certain distance behind the face.

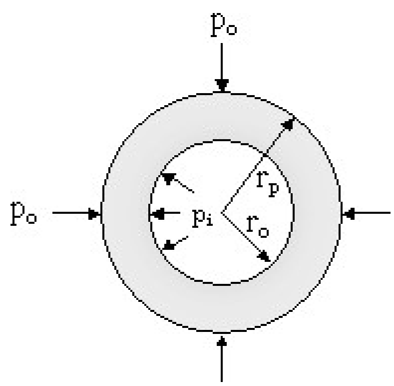
Note that plastic failure of the rock mass surrounding a tunnel does not necessarily mean that the tunnel collapses. The failed material can still have considerable strength, and provided that the thickness of the plastic zone is small compared with the tunnel radius, the only evidence of failure may be a few fresh cracks and a minor amount of raveling or spalling.

On the other hand, when a large plastic zone is formed and when large inward displacements of the tunnel wall occur, the loosening of the failed rock mass can lead to severe spalling and raveling and eventual collapse of an unsupported tunnel.

The primary function of support is to control the inward displacement of the walls and to prevent the loosening, which can lead to collapse of the tunnel. The installation of support (e.g. rockbolts, shotcrete lining, or steel sets) cannot prevent failure of the rock surrounding a tunnel subjected to significant overstressing, but these support types do play a major role in controlling tunnel deformation (Hoek et. al. 1995).

Ground Reaction Curve

At the heart of the "rock support interaction" analysis method used in *RocSupport*, is the "ground reaction curve" or "characteristic line," which relates internal support pressure to tunnel wall convergence. The general derivation of the ground reaction curve, is as follows.



Assume that a circular tunnel of radius r_o is subjected to hydrostatic in-situ stress p_o and a uniform internal support pressure p_i, as illustrated in the margin figure.

Failure of the rock mass surrounding the tunnel occurs when the internal pressure provided by the tunnel lining is less than a critical support pressure p_{cr}.

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

$$u_{ie} = \frac{r_o(1+\nu)}{E}(p_o - p_i) \quad \text{Eqn. 1.1}$$

When the internal support pressure p_i is less than the critical support pressure p_{cr}, failure occurs and a plastic zone of radius r_p is formed around the tunnel. The inward radial plastic displacement u_{ip} is then defined by the ground reaction curve between $p_i = p_{cr}$ and $p_i = 0$.

A typical ground reaction curve is shown in Figure 1-3.

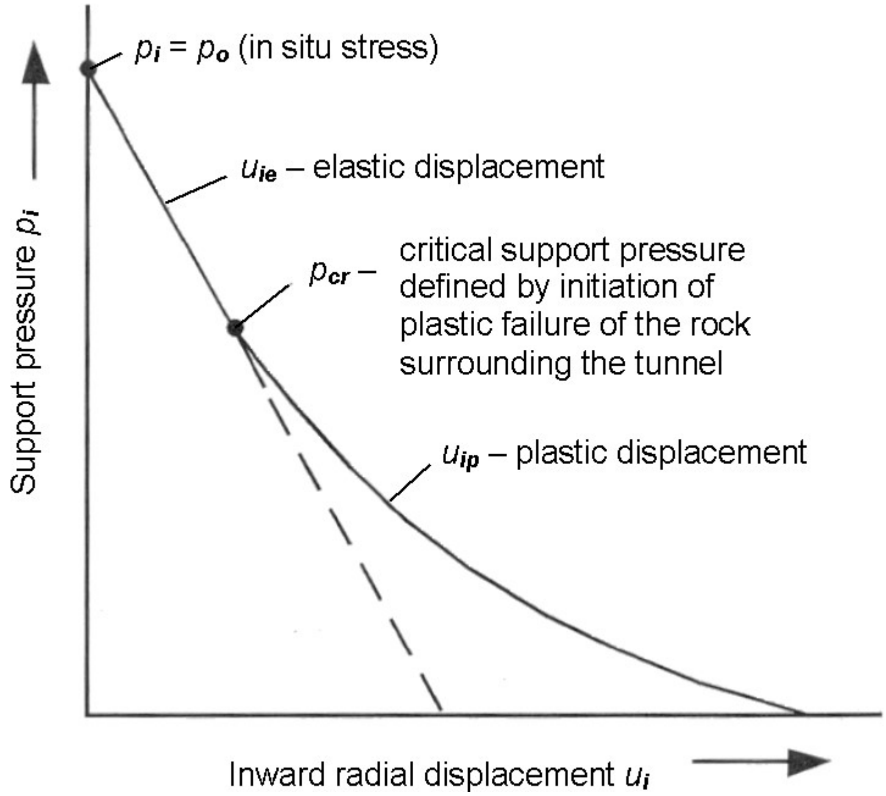


Figure 1-3: Ground reaction curve showing relationship between support pressure and tunnel wall convergence (Hoek et. al. 1995).

This plot shows:

- zero displacement when the support pressure equals the hydrostatic stress ($p_i = p_o$)
- elastic displacement u_{ie} for $p_o > p_i > p_{cr}$
- plastic displacement u_{ip} for $p_i < p_{cr}$
- maximum displacement when the support pressure equals zero

For a given tunnel radius and in-situ stress, the shape of the ground reaction curve depends on the rock mass failure criterion which is assumed and the specific rock mass characteristics.

The following are dependent on the rock mass failure criterion and characteristics:

- the critical support pressure p_{cr}
- the radius of the plastic zone r_p
- the shape of the ground reaction curve in the plastic region ($p_i < p_{cr}$)

See the Solution Methods topic, later in this Introduction, for an overview of the different solution methods used in *RocSupport*. These correspond to Mohr-Coulomb or Hoek-Brown rock mass failure criteria, and have been derived for the rock support interaction problem.

Support Reaction

In order to complete the rock support interaction analysis, the reaction curve for the rock support must be determined. This is a function of three components:

1. The tunnel wall displacement that has occurred before the support is installed.
2. The stiffness of the support system.
3. The capacity of the support system.

Referring back to Figure 1-1, remember that a certain amount of deformation takes place ahead of the advancing face of the tunnel. At the face itself, approximately one-third of the total deformation has taken place, and this cannot be recovered. In addition, there is almost always a stage of the excavation cycle in which there is a gap between the face and the closest installed support element. Therefore, further deformation occurs before the support becomes effective. This total initial displacement will be called u_{so} and is shown in Figure 1-4.

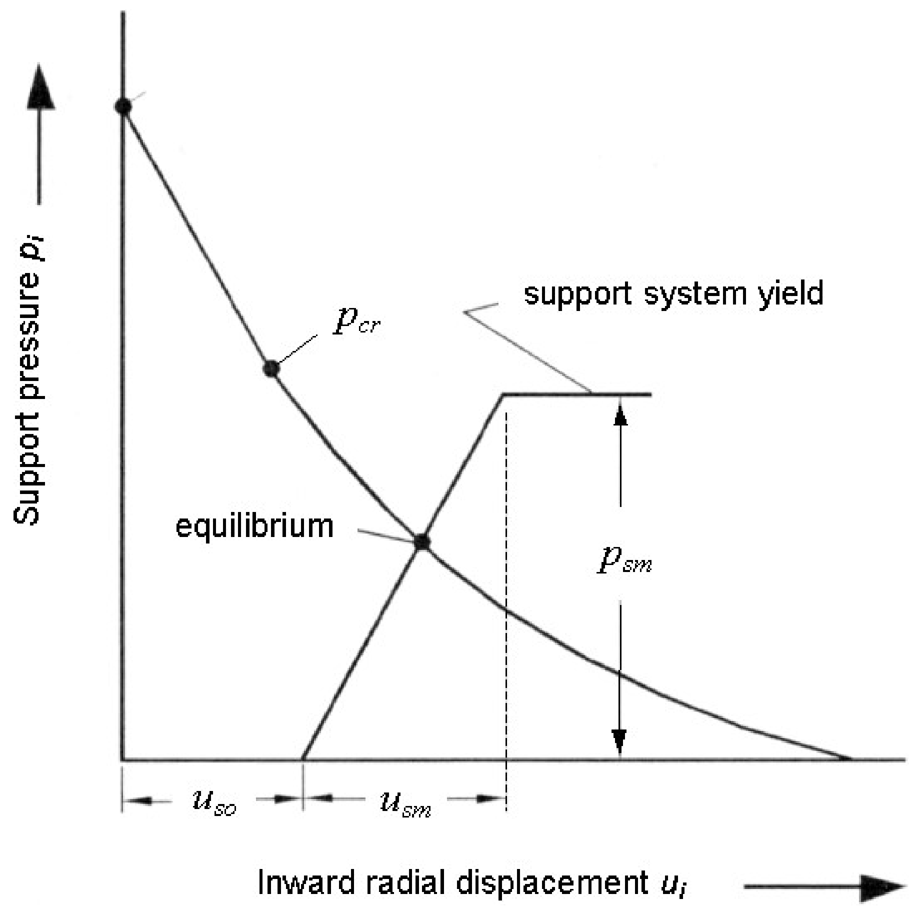


Figure 1-4: Response of support system to tunnel wall displacement, resulting in establishment of equilibrium (Hoek et.al. 1995).

Once the support has been installed and is in full and effective contact with the rock, the support starts to deform elastically as shown in Figure 1-4. The maximum elastic displacement which can be accommodated by the support system is u_{sm} and the maximum support pressure p_{sm} is defined by the yield of the support system.

Depending upon the characteristics of the support system, the rock mass surrounding the tunnel and the in-situ stress level, the support system will deform elastically in response to the closure of the tunnel, as the face advances away from the point under consideration.

Rock-Support Equilibrium

Equilibrium is achieved if the support reaction curve intersects the rock mass displacement curve before either of these curves have progressed too far. If the support is installed too late (i.e. u_{so} is large in Figure 1-4), the rock mass may have already deformed to the extent that loosening of the failed material is irreversible. On the other hand, if the capacity of the support is inadequate (i.e. p_{sm} is low in Figure 1-4), then yield of the support may occur before the rock mass deformation curve is intersected. In either of these cases the support system will be ineffective, since the equilibrium condition, illustrated in Figure 1-4, will not have been achieved.

Support Characteristics

In *RocSupport*, the stiffness and capacity of support is expressed in terms of Maximum Support Pressure and Maximum Support Strain. In this form it is incorporated directly into the rock support interaction analysis.

Note that since the support capacity is simply modeled as an equivalent internal pressure, the reinforcement provided by grouted rockbolts or cables cannot be properly accounted for in this simple model. However, the radius of the plastic zone calculated from the analysis, can be used as a guide for the length of bolts or cables – i.e. bolts or cables should always be anchored in unyielded rock.

The stiffness and capacity of support systems such as rockbolts, steel sets, shotcrete and of combinations of these elements can be estimated from relatively simplistic analyses published in Hoek and Brown (1980) and summarized in Hoek (1999b). These estimates have been used for the pre-defined support types available in *RocSupport*.

Support Installation

The origin of the support reaction curve in Figure 1-4 (i.e. the value of u_{so}), is the tunnel convergence which has occurred at the point of support installation. In *RocSupport*, this value can be specified in two ways:

- directly (as a convergence or wall displacement), or
- indirectly (a distance from the tunnel face is specified, which is then converted to tunnel convergence using a longitudinal tunnel deformation profile)

In *RocSupport* you can choose from a pre-defined longitudinal deformation profile (LDP) function, or create a user-defined LDP function. An example of one of the pre-defined LDP functions is shown in Figure 1-5

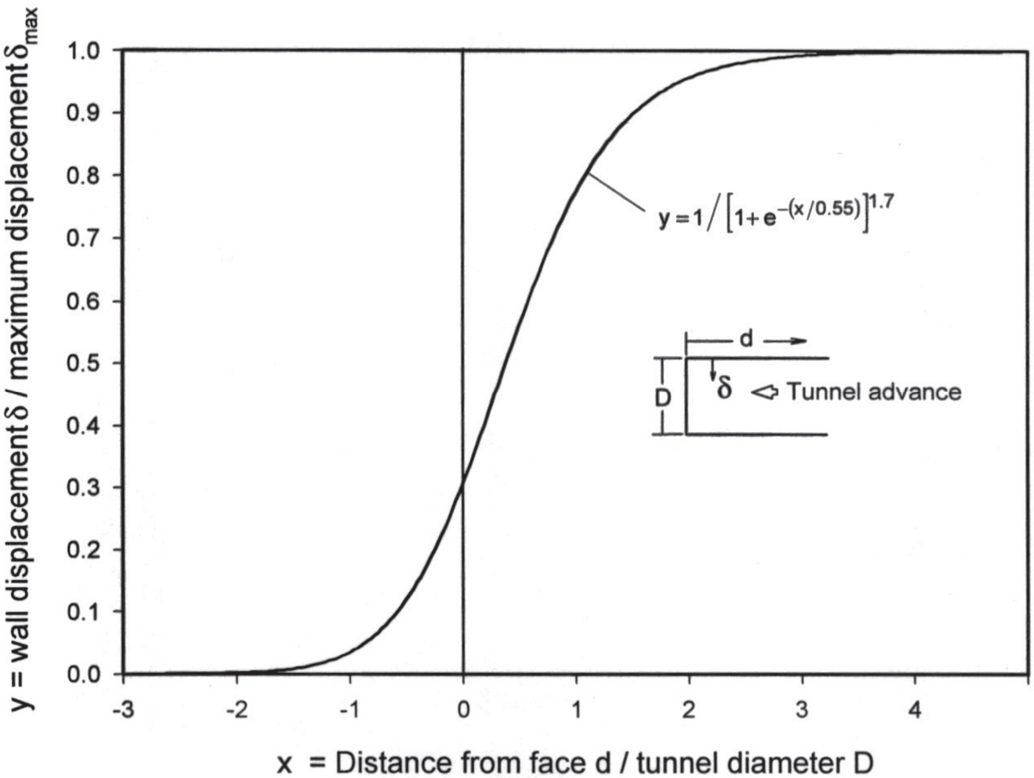


Figure 1-5: Tunnel wall displacement as a function of distance from face (Hoek, 1999a).

Determination of the tunnel wall displacement that has occurred before the support is installed is not a trivial problem, since it involves a consideration of the three-dimensional stress distribution, and propagation of failure surrounding the advancing face. The latest method published by Vlachopolous and Diederichs (2009) is currently the default LDP function in *RocSupport*. Other approaches are found in Chern et al (1998), Panet (1995) and Unlu and Gercek (2003).

Solution Methods

A number of derivations of the "rock support interaction" analysis method have now been published. All methods assume a circular tunnel in a hydrostatic stress field, and the main theoretical efforts have been devoted to the calculation of the size of the plastic zone, and the shape of the ground reaction curve, for different assumptions on how the failure of the rock mass progresses as the tunnel is advanced.

The main differences between the various methods used to calculate the ground reaction curve, are in the choice of the rock mass failure criterion, and in whether or not the rock mass dilates (changes in volume) during failure.

In *RocSupport*, the following solution methods are available:

- Duncan Fama (1993)
- Carranza-Torres (2004)
- Vrakas and Anagnostou (2014)
- Lee and Pietruszczak (2008)
- Barbosa (2009)
- Vrakas (2016)

All are closed-form solutions, but with slightly different approaches and assumptions. In the Project Settings dialog, a small description of each solution method is displayed to the right of the Solution Method section once a specific method has been selected. See the references for details about each solution method.

Deterministic Analysis

In the Project Settings dialog, the user can choose either Deterministic or Probabilistic analysis types.

A Deterministic analysis simply means that all input variables are assumed to be "exactly" known (e.g. in-situ stress and rock strength parameters).

This results in a unique solution for all program output, including:

- the Ground Reaction curve
- Plastic Zone Radius
- Equilibrium pressure (if support is installed)
- Factor of Safety (for support)

Factor of Safety

A unique Factor of Safety for the support is calculated in a Deterministic analysis. The definition of the Factor of Safety in *RocSupport* is as follows:

A Factor of Safety GREATER THAN 1 is calculated as shown in Figure 1-6. In this case the Factor of Safety is simply the ratio of the Maximum Support Pressure p_{sm} to the Equilibrium Pressure p_{eq} (the pressure at the intersection point of the Ground Reaction and Support Reaction curves).

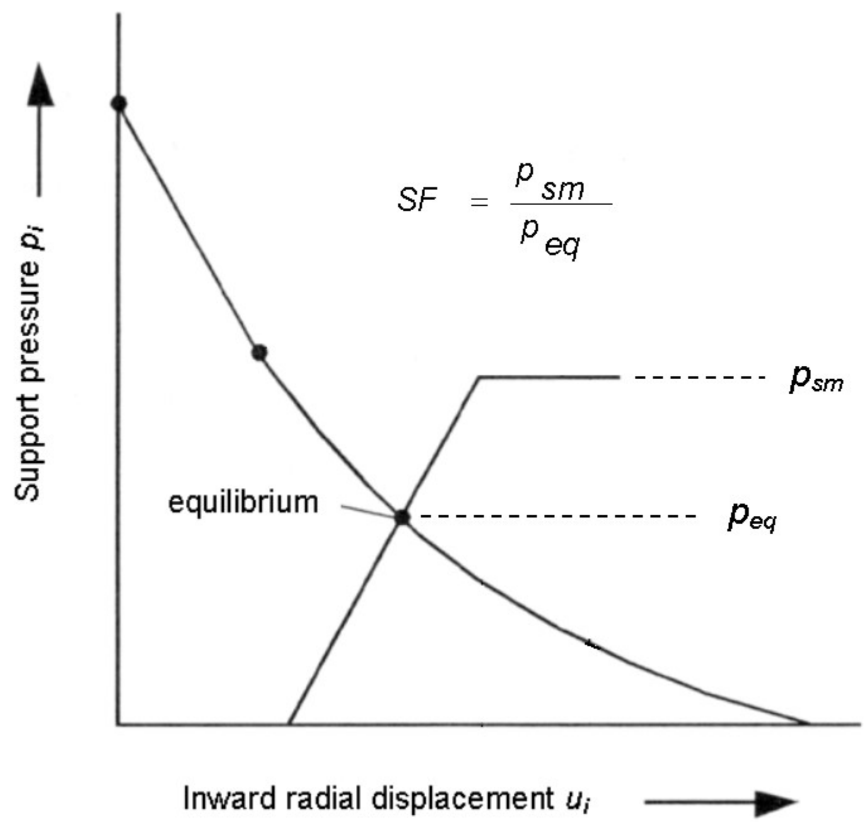


Figure 1-6: Definition of Factor of Safety > 1.

A Factor of Safety LESS THAN 1 is calculated as shown in Figure 1-7. This occurs when the Ground Reaction curve intersects the Support Reaction curve after the elastic limit of the support has been exceeded. A "projected" equilibrium pressure p'_{eq} is calculated by projecting the elastic support reaction curve until it intersects the Ground Reaction curve, and this value is used in the denominator of the Factor of Safety equation.

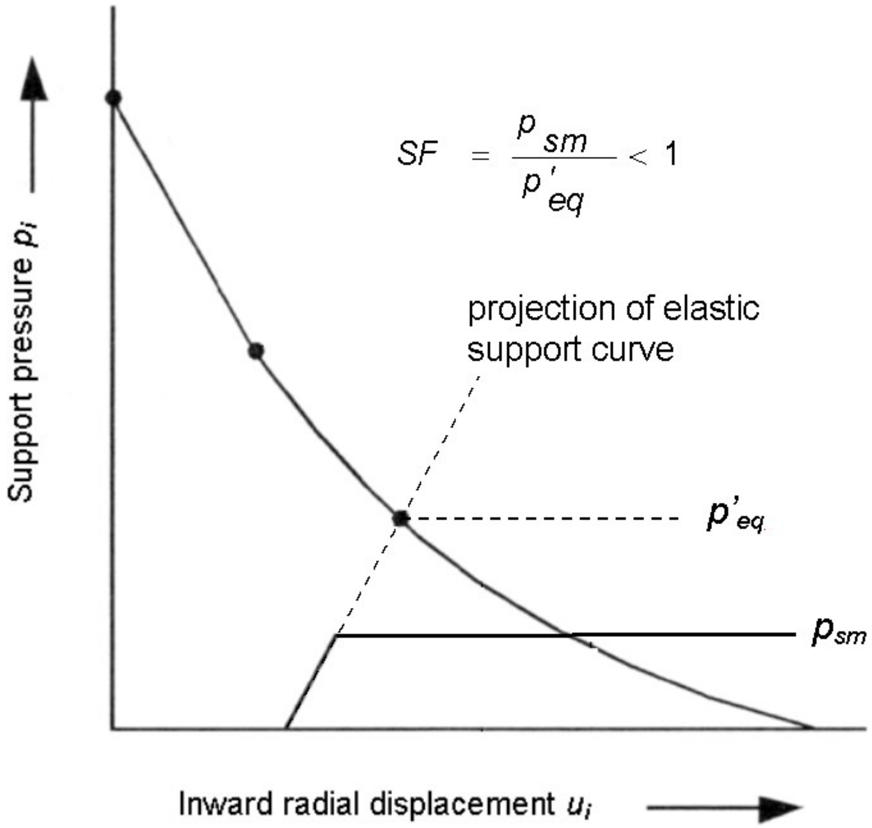


Figure 1-7: Definition of Factor of Safety < 1

Probabilistic Analysis

In the Project Settings dialog, the user can choose either Deterministic or Probabilistic analysis types.

A Probabilistic analysis allows the user to input statistical distributions for:

- tunnel radius
- in-situ stress
- all rock mass parameters

Using either Monte Carlo or Latin Hypercube sampling, the program will then sample the input distributions and run the analysis for the specified Number of Samples defined by the user in the Project Settings dialog.

The user can then view statistical distributions of all output variables (e.g. plastic zone radius, wall displacement), rather than simply a single number as calculated from a Deterministic analysis.

Probability of Failure

A Probabilistic analysis results in a distribution of Safety Factor, rather than a single value. From a Safety Factor distribution, a Probability of Failure can be calculated.

The Probability of Failure in *RocSupport* is simply the number of analyses with Safety Factor less than 1, divided by the total number of analyses generated by the Probabilistic analysis.

For example, if 100 out of 1000 samples in a Probabilistic analysis resulted in a Factor of Safety less than 1, then the Probability of Failure would be 10 %.

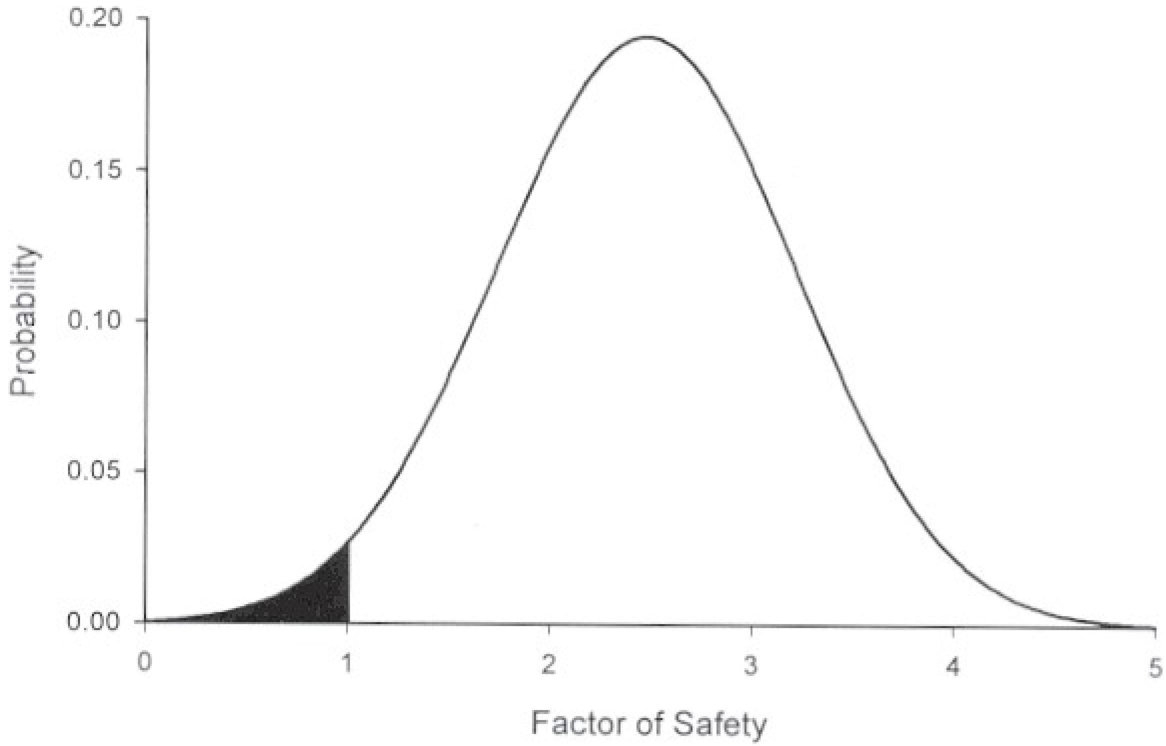


Figure 1-8: Definition of Probability of Failure.

Mathematically speaking, the Probability of Failure is the area under the Factor of Safety probability distribution to the LEFT of Factor of Safety = 1 (i.e. the black area in Figure 1-8), divided by the total area under the curve.

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