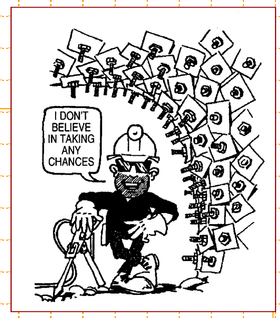
EOSC433:

Geotechnical Engineering Practice & Design

Lecture 9: Rock Stabilization Principles



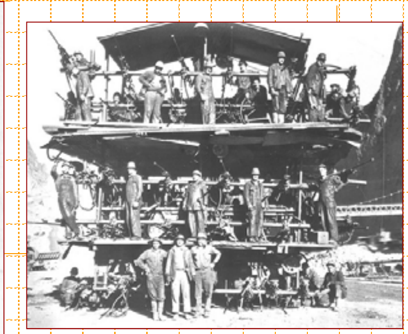
Building on Past Experiences – Worker Safety

Boys working during World War I coal boom.

Photograph from U. S. Bureau of Mines

A TINY GUARDIAN OF THE MINER'S WELFARE

As susceptible as men are to the overwhelming effects of mine gases, the canary bird is much more so. The result is that in many disasters the birds are made the outposts of the invading army of restoration. They are overcome long before man can detect the presence of the gas and therefore warn the men of the dangers ahead.



Building on Past Experiences – Ground Control

Photograph from U. S. Bureau of Mines

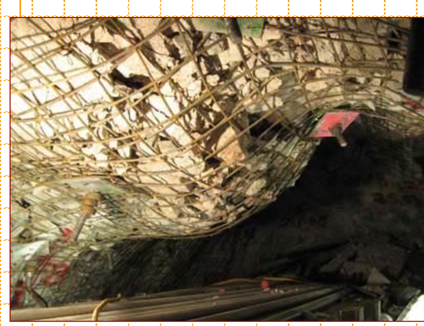
LINING A MINE WALL WITH ARTIFICIAL ROCK

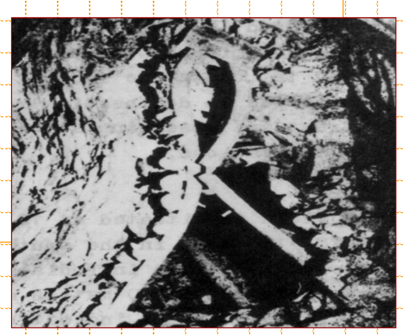
One of the frequent causes of mine cave-ins is the weathering of the slate of the roof and side walls. It gradually crumbles or scales off and suffers a consequent weakening, which may finally bring disaster. The cement gun covers the slate with a thin plaster, which effectually shuts out the air and leaves it as unexposed to deterioration as it was during the countless ages before the coal was removed.

Effect of Excavation on Rock Mass

When considering the principles of rock mass stabilization, there are two aspects of rock excavation that must be considered:

- **The first is that one cannot prevent <u>all</u> displacements at the excavation boundary (however, limiting these is advantageous).**
- **The second is that mistakes in excavation design can lead to major problems… rock under stress is very unforgiving.**



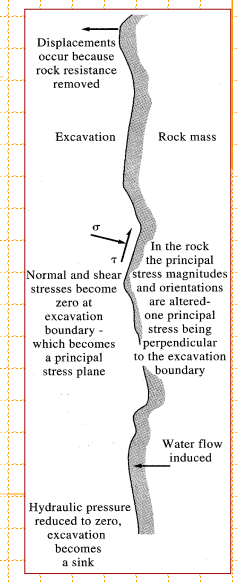


Effect of Excavation on Rock Mass

Displacements: the engineering objective dictates the significance of any rock displacement and its maximum tolerable magnitude. It is important to know whether the displacements are associated with entire rock blocks moving into the excavation, whether the rock mass is deforming as a whole, or whether failure is occurring in the rock.

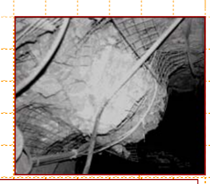
Stress Field: the significance of stress field disturbance is that rock is more likely to fail, owing to the increased magnitude of the deviatoric stresses.

Water Flow: increased water flow is significant because there will be higher differential heads within the rock mass which tend to push rock blocks into the excavation, with the attendant possibility of increased weathering and time dependent deterioration.



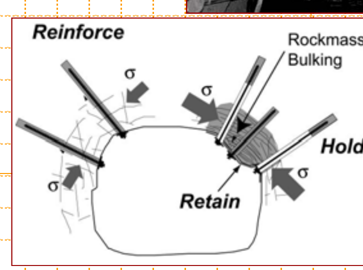
The Stabilization Strategy

The effects of excavation (displacements, stress changes, etc.), and the optimal stabilization strategy to account for them, should not blindly attempt to maintain the original conditions (e.g. by installing massive support or reinforcement and hydraulically sealing the entire excavation). As the displacements occur, engineering judgement may determine that they can be allowed to develop fully, or be controlled later.



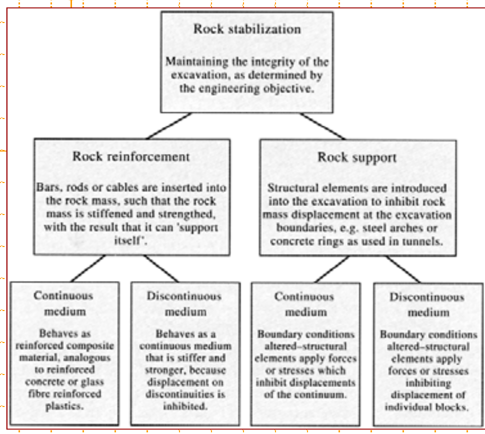
Reinforcement: the primary objective is to mobilize and conserve the inherent strength of the rock mass so that it becomes self-supporting.

Support: the primary objective is to truly support the rock mass by structural elements which carry, in whole or part, the weights of individual rock blocks isolated by discontinuities or of zones of loosened rock.

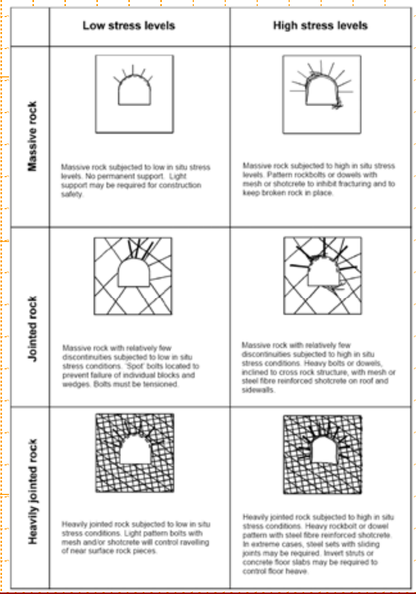


Kaiser *et al.* (2000)

Stabilization Strategy & Rock Mass Conditions



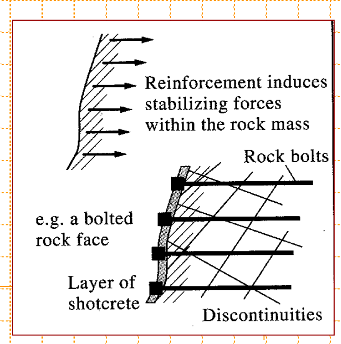
Hudson & Harrison (1997)



Hoek *et al.* (1995)

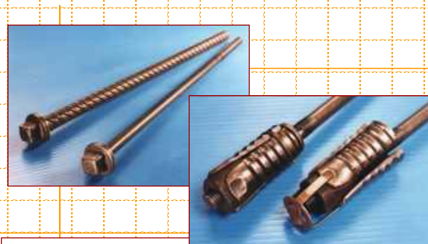
The Stabilization Strategy - Reinforcement

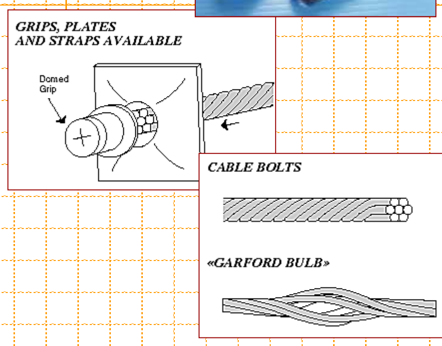
In the case of reinforcement, steel cables or bolts grouted within boreholes are used to minimize displacements occurring along the discontinuities – *so that the rock supports itself*. In conjunction with bolting, sprayed concrete (shotcrete) is used to protect the surface and inhibit minor block movements.

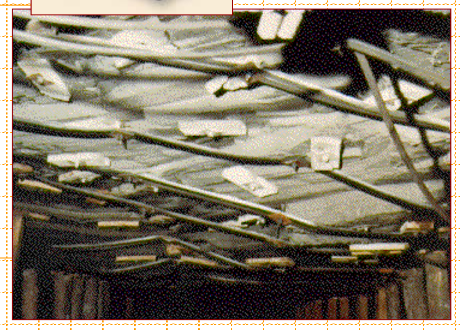


Hudson & Harrison (1997)

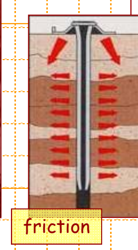
Rock Reinforcement

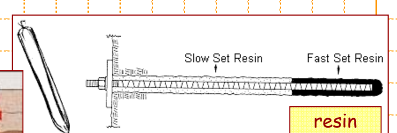


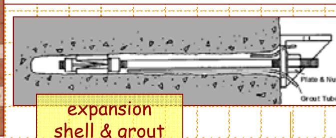


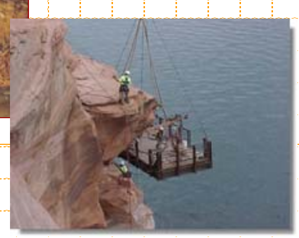


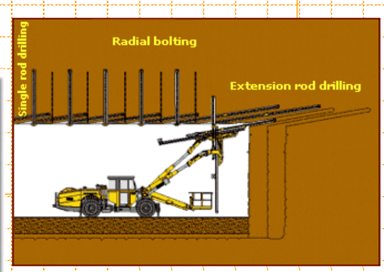
Rock Reinforcement - Installation





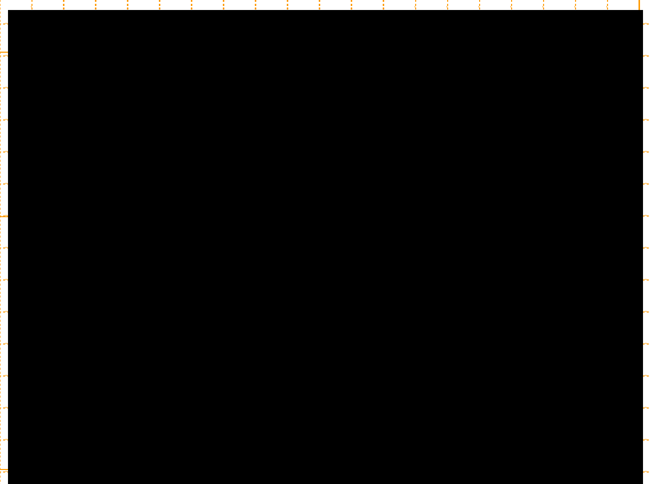






Rock Reinforcement Installation

SWELLEX bolts:
- *grips to the irregularities of the drilled hole and gives immediate full loading capacity.*
- *can accommodate large ground movement and shear displacement.*
- *manual installation is easy, fast and does not require heavy equipment.*
- *insensitive to blasting and variations in bore hole diameter.*



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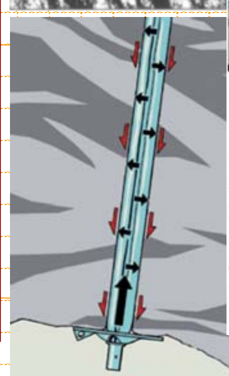
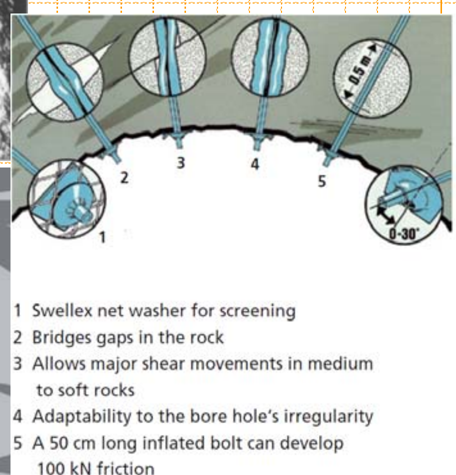
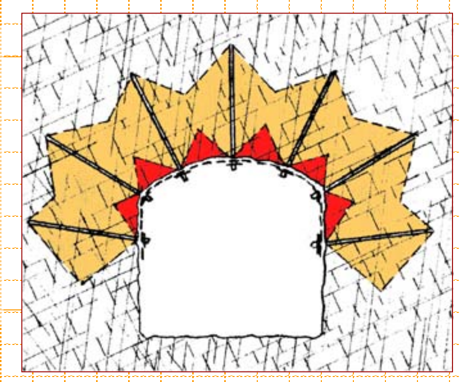




Rock Reinforcement in Jointed Rock

In jointed rock (discontinuous medium), the mode of action of the reinforcement is not only to modify and improve the rock mass strength and deformation characteristics, but also to avoid large displacements of complete blocks (e.g., wedges).

Two of the most important factors are whether the blocks are free to move, given the geometry of the rock mass and excavation (i.e. kinematic feasibility), and the characteristics of the reinforcement (quantity, length, orientation, etc.).



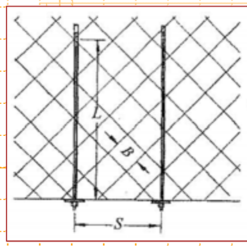
Hoek *et al.* (1995)

Rock Reinforcement in Jointed Rock

Considering now the length and diameter of the bolt, these have to ensure that the strength of the bonds across the anchor-grout and grout-rock interfaces are capable of sustaining the necessary tension in the anchor, which in turn will depend on the bulking of the rock mass. The required anchor capacity can be met through the selection of its diameter relative to the tensile strength of the anchor material.

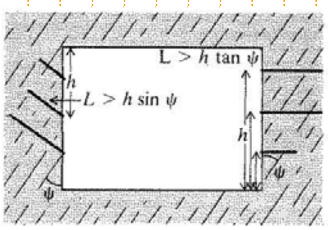
Empirical Guidelines

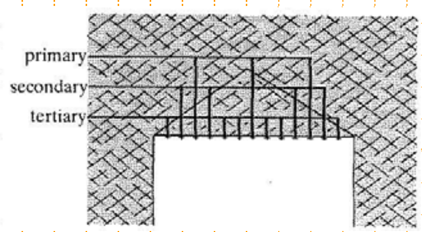
Lang (1961), Snowy Mountains Electrical Scheme in Australia:



Maximum bolt spacing:
At least 0.5L and 1.5B

Minimum bolt length:
2 x bolt spacing
3 x width of wedge defined by joint spacing, B
0.5B for spans <6 m, 0.25B for spans 18-30 m.





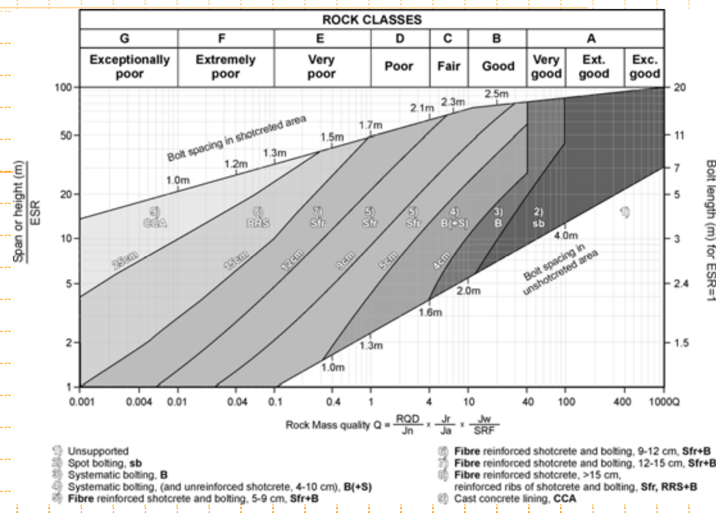
Empirical Guidelines

Bieniawski (1989), South African rock tunnels:

Rock mass class	Excavation	Rock bolts (20 mm diameter, fully grouted)	Shotcrete	Steel sets
I – Very good rock *RMR*: 81-100	Full face, 3 m advance	Generally no support required except spot bolting		
II – Good rock *RMR*: 61-80	Full face , 1-1.5 m advance. Complete support 20 m from face	Locally, bolts in crown 3 m long, spaced 2.5 m with occasional wire mesh	50 mm in crown where required	None
III – Fair rock *RMR*: 41-60	Top heading and bench 1.5-3 m advance in top heading. Commence support after each blast. Complete support 10 m from face	Systematic bolts 4 m long, spaced 1.5-2 m in crown and walls with wire mesh in crown	50-100 mm in crown and 30 mm in sides	None
IV – Poor rock *RMR*: 21-40	Top heading and bench 1.0-1.5 m advance in top heading. Install support concurrently with excavation, 10 m from face	Systematic bolts 4-5 m long, spaced 1-1.5 m in crown and walls with wire mesh	100-150 mm in crown and 100 mm in sides	Light to medium ribs spaced 1.5 m where required
V – Very poor rock *RMR*: < 20	Multiple drifts 0.5-1.5 m advance in top heading. Install support concurrently with excavation. Shotcrete as soon as possible after blasting	Systematic bolts 5-6 m long, spaced 1-1.5 m in crown and walls with wire mesh. Bolt invert	150-200 mm in crown, 150 mm in sides, and 50 mm on face	Medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required. Close invert

Empirical Guidelines

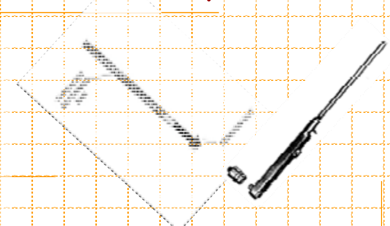
Grimstad & Barton (1988), Norwegian rock tunnels:



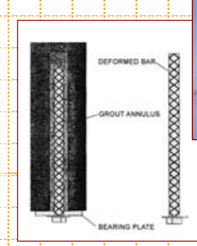
Active and Passive Reinforcement

Rock reinforcement may be classified as active or passive:

Active reinforcement is installed with a predetermined load to the rock surface (e.g. tensioned cables or bolts). This is usually favoured when it is necessary to support the gravity loads imposed by individual rock blocks.

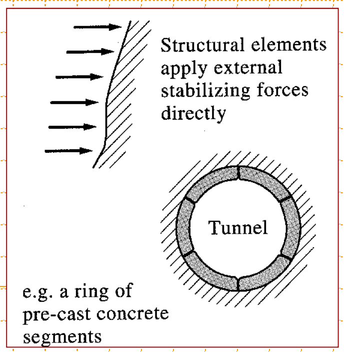


Passive reinforcement is not installed with an applied load, but rather develops its loads as the rock mass deforms (e.g. grouted bars, friction bolts, shotcrete, wire mesh). Passive reinforcement therefore requires rock displacement to function.



The Stabilization Strategy - Support

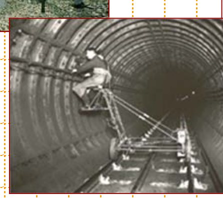
In the case of support/retainment, structural elements – such as steel arches or concrete rings – are introduced to inhibit rock displacements at the boundary of the excavation. These elements, which are external to the rock mass, provide load bearing capability, with the result that – *the rock is partially supported*.



Hudson & Harrison (1997)

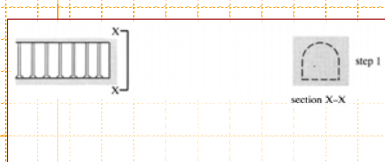
Rock Support

… passive and active crib support



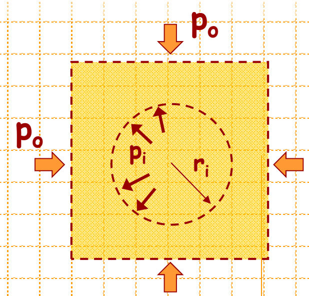
Rock Support Principles

Consider a tunnel being advanced by conventional methods, where steel sets are installed after each drill & blast cycle.



Daemen (1977)

In **Step 1**: the heading has not reached X-X and the rock mass on the periphery of the future tunnel profile is in equilibrium with the internal pressure (p_i) acting equal and opposite to p_o.



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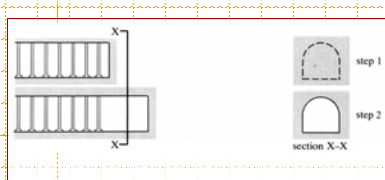
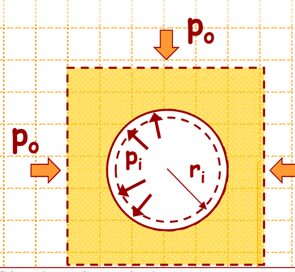
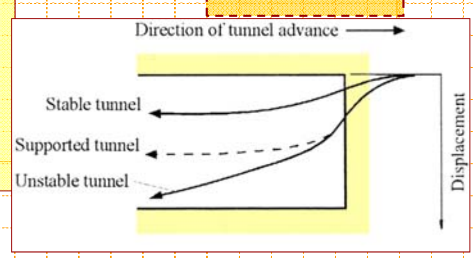


Daemen (1977)

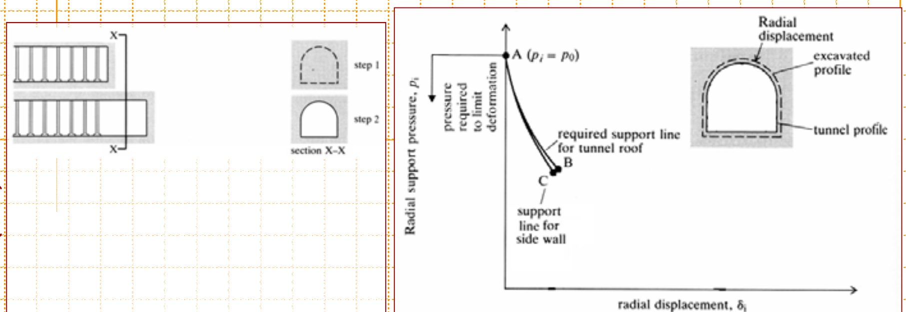
In **Step 2**: the face has advanced beyond X-X and the support pressure (p_i) provided by the rock inside the tunnel has been reduced to zero. As the blasted rock must be removed before the steel sets (support) can be installed, deformation of the excavation boundaries starts to occur.





Tunnel Support Principles

We can then plot the radial support pressure (p_i) required to limit the boundary displacement (δ_i) to a given value.



Daemen (1977)

Thus, by advancing the excavation and removing the internal support pressure provided by the face, the tunnel roof will converge and displace along line AB (or AC in the case of the tunnel walls; the roof deformation follows a different path due to the extra load imposed by gravity on the loosened rock in the roof).

Tunnel Support Principles

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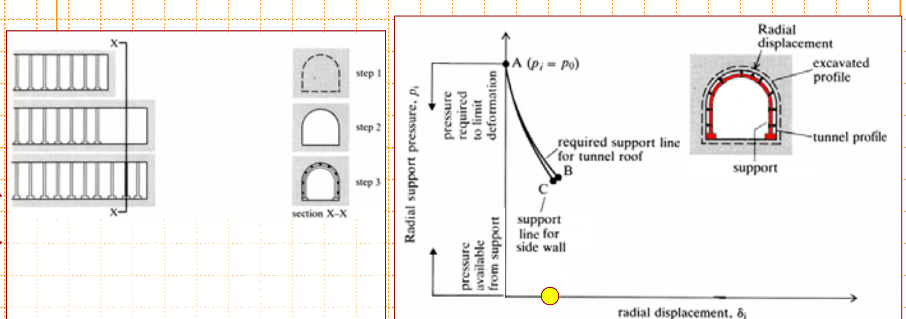


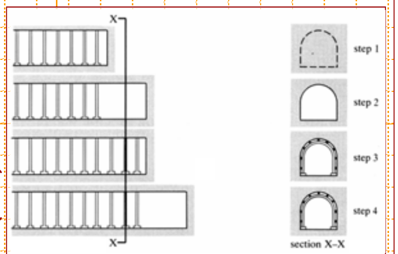
Daemen (1977)

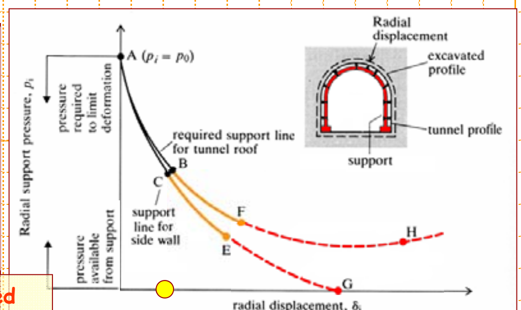
By <u>Step 3</u>: the heading has been mucked out and steel sets have been installed close to the face. At this stage the sets carry no load, but from this point on, any deformation of the tunnel roof or walls will result in loading of the steel sets.

Tunnel Support Principles

We can then plot the radial support pressure (p_i) required to limit the boundary displacement (δ_i) to a given value.

Daemen (1977)





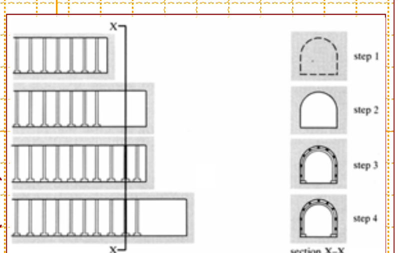
In **Step 4**: the heading is advanced one and a half tunnel diameters beyond X-X by another blast. The restraint offered by the proximity of the face is now negligible and further convergence of the tunnel boundaries occurs.

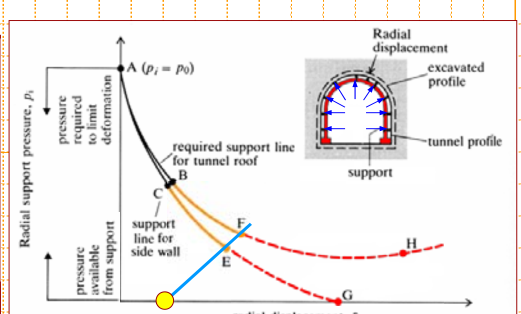
If steel sets had not been installed, the radial displacements at X-X would continue increasing along the dashed lines EG and FH. In this case, the side walls would reach equilibrium at point G. However, the roof would continue deforming until it failed.

Tunnel Support Principles

We can then plot the radial support pressure (p_i) required to limit the boundary displacement (δ_i) to a given value.

Daemen (1977)





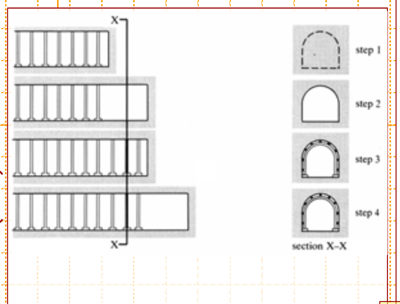
... but with steel sets installed, the tunnel convergence will begin to load the support.

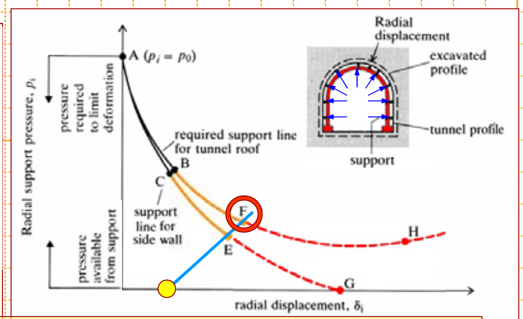
This load path is known as the **support reaction line** (or available support line). The curve representing the behaviour of the rock mass is known as the **ground response curve** (or support required curve).

Tunnel Support Principles

We can then plot the radial support pressure (p_i) required to limit the boundary displacement (δ_i) to a given value.

Daemen (1977)



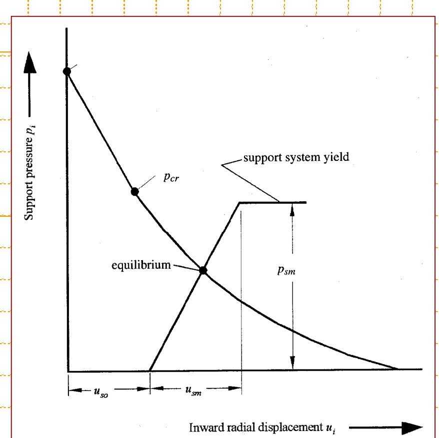


Equilibrium between the rock and steel sets is reached where the lines intersect.

It is important to note that most of the redistributed stress arising from the excavation is carried by the rock and not by the steel sets!!

Ground Response & Support Reaction Curves

If support is required, we can gain an indication of the efficacy of particular support systems by plotting the elastic behaviour of the support, the available support line, on the same axes as the ground response curve. The points of interest are where the available support lines intersect the ground response curves: at these points, equilibrium has been achieved.



Hoek *et al.* (1995)

Worked Example: Rock-Support Interaction

Q. A circular tunnel of radius 1.85 m is excavated in rock subjected to an initial hydrostatic stress field of 20 MPa and provided with a concrete lining of internal radius 1.70 m. Assuming elastic behaviour of the rock/lining, calculate/plot the radial pressure and the radial displacement at the rock lining interface if the lining is installed after a radial displacement of 1 mm has occurred at the tunnel boundary.

A. Given:

$$u_r = -\frac{pa}{2G}$$

$$p_r = k\frac{u_r - u_o}{a}$$

$$k = \frac{E_c}{1+\nu_c}\frac{a^2-(a-t_c)^2}{(1-2\nu_c)a^2+(a-t_c)^2}$$

- p = hydrostatic stress
- a = tunnel radius
- G = shear modulus (assume 2 GPa)
- p_r = radial support pressure
- k = lining stiffness
- u_o = rock displacement when support installed
- t_c = concrete lining thickness
- E_c = lining elastic modulus (assume 30 GPa)
- ν_c = lining Poisson ratio (assume 0.25)

Worked Example: Rock-Support Interaction

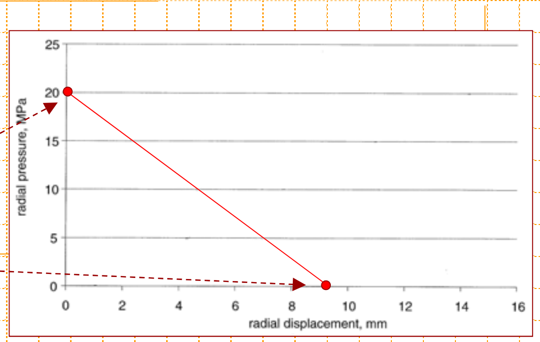
A. To find the ground response curve we need to identify the two end points of the line: one is the *in situ* condition of zero displacement at a radial stress of 20 MPa, the other is the maximum elastic displacement induced when the radial stress is zero.

① $$u_r = \frac{pa}{2G} \Rightarrow u_r = \frac{(20e6\,Pa)(1.85m)}{2\cdot(2e9\,Pa)} = 0.00925m$$

② Plotting our ground response line, we have two known points:

$p_r = 20\ MPa$, $u_r = 0\ mm$

$p_r = 0\ MPa$, $u_r = 9.25\ mm$



Harrison & Hudson (2000)

Worked Example: Rock-Support Interaction

A. To find the support reaction line, we assume the lining behaves as a thick-walled cylinder subject to radial loading. The equation for the lining characteristics in this case is:

$$k = \frac{E_c}{1+\nu_c}\frac{a^2-(a-t_c)^2}{(1-2\nu_c)\,a^2+(a-t_c)^2}$$

③ Solving for the stiffness of the lining, where t_c = 1.85 – 1.70 = 0.15 m, E_c = 30 GPa and ν_c = 0.25, we get:

$$k = \frac{30\,GPa}{1+0.25}\left[\frac{(1.85m)^2-(1.85m-0.15m)^2}{(1-0.5)(1.85m)^2+(1.85m-0.15m)^2}\right]$$

$$k = \underline{\underline{2.78\,GPa}}$$

Worked Example: Rock-Support Interaction

A. ③ Thus, for a radial pressure of 20 MPa and u_o = 1 mm, the lining will deflect radially by:

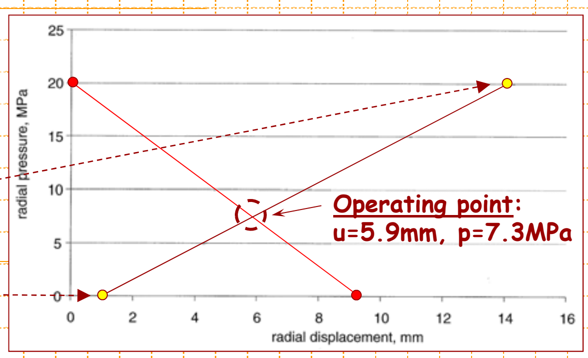
$$p_r = k\frac{u_r-u_o}{a} \Rightarrow u_r = \frac{a}{k}p_r + u_o = \frac{1.85m}{2.78e9\,Pa}20e6\,Pa + 0.001\,m$$

$$u_r = \underline{\underline{0.014\,m}}$$

④ Plotting our support reaction line, we have two known points:

$p_r = 20\,MPa$
$u_r = 0.014\,mm$

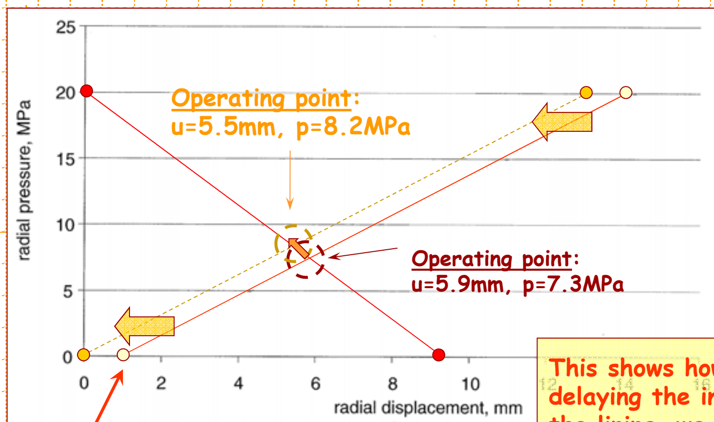
$p_r = 0\,MPa$
$u_r = 1\,mm$



Harrison & Hudson (2000)

Worked Example: Rock-Support Interaction

Harrison & Hudson (2000)



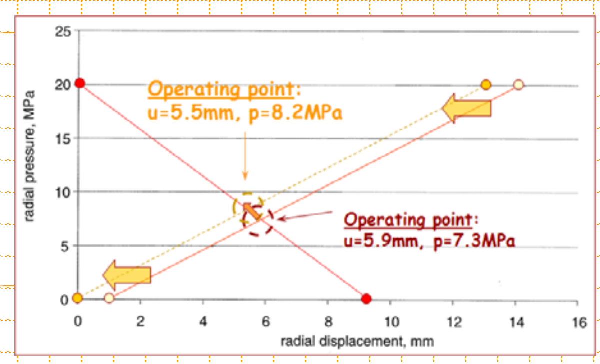
1 mm displacement of tunnel boundary before lining is installed

This shows how, by delaying the installation of the lining, we can reduce the pressure it is required to withstand – but at the expense of increasing the final radial displacement.

Rock Support in Yielding Rock

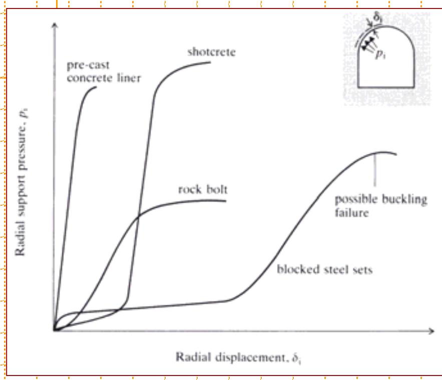
Thus, it should never be attempted to achieve zero displacement by introducing as stiff a support system as possible – this is never possible, and will also induce unnecessarily high support pressures. The support should be in harmony with the ground conditions, with the result that an optimal equilibrium position is achieved.

In general, it is better to allow the rock to displace to some extent and then ensure equilibrium is achieved before any deleterious displacement of the rock occurs.



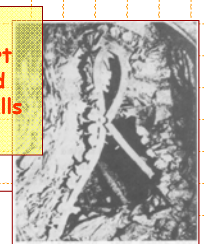
Rock Support in Yielding Rock

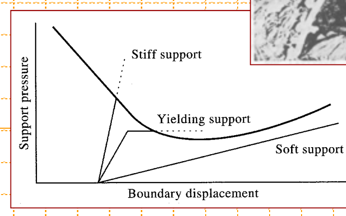
Another important conclusion drawn from these curves, for the case of unstable non-elastic conditions, is that stiff support (e.g. pre-cast concrete segments) may be successful, but that soft support (e.g. steel arches) may not bring the system to equilibrium.



Brady & Brown (2006)

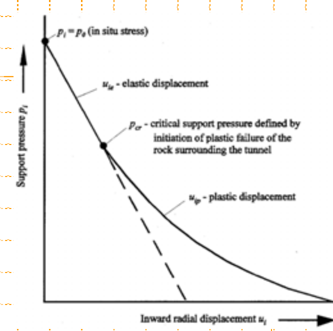
One of the primary functions of the support is to control the inward displacement of the walls to prevent loosening.





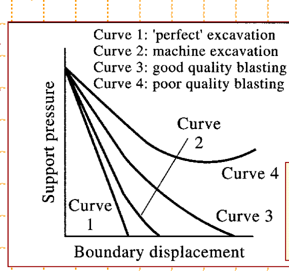
Ground Response Curve – Yielding Rock

It should also be noted that plastic failure of the rock mass does not necessarily mean collapse of the tunnel. The yielded rock may still have considerable strength and, provided that the plastic zone is small compared with the tunnel radius, the only evidence of failure may be some minor spalling. In contrast, when a large plastic zone forms, large inward displacements may occur which may lead to loosening and collapse of the tunnel.



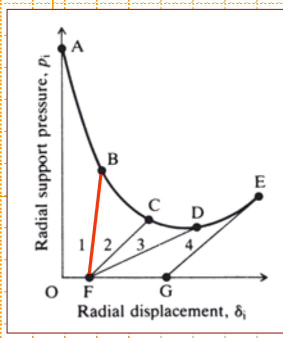
Hoek *et al.* (1995)

Hudson & Harrison (1997)



Effect of excavation methods on shape of the ground response curve due induced damage and alteration of rock mass properties.

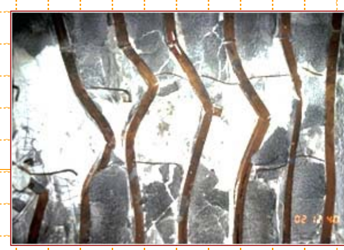
Summary: Rock Support in Yielding Rock



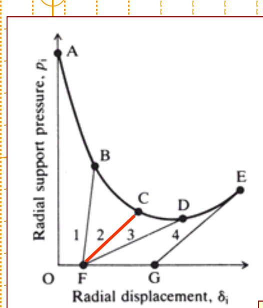
Brady & Brown (2006)

Support 1 is installed at *F* and reaches equilibrium with the rock mass at point *B*:

This support is too stiff for the purpose and attracts an excessive share of the redistributed load. As a consequence, the support elements may fail causing catastrophic failure of the rock surrounding the excavation.



Rock Support in Yielding Rock

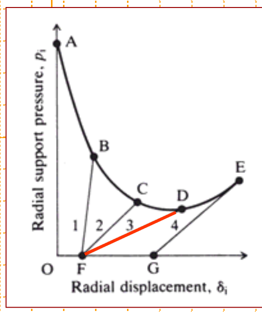


Support 2, having a lower stiffness, is installed at *F* and reaches equilibrium with the rock mass at point *C*:

Provided the corresponding convergence of the excavation is acceptable operationally, this system provides a good solution. The rock mass carries a major portion of the redistributed load, and the support elements are not stressed excessively.

Note that if this support was temporary and was to be removed after equilibrium had been reached, uncontrolled displacement and collapse of the rock mass would almost certainly occur.

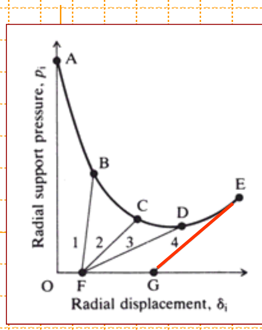
Rock Support in Yielding Rock



Support 3, having a much lower stiffness than support 2, is also installed at *F* but reaches equilibrium with the rock mass at point *D* where the rock mass has started to loosen:

Although this may provide an acceptable temporary solution, the situation is a dangerous one because any extra load imposed, for example by a redistribution of stress associated with the excavation of a nearby opening, will have to be carried by the support elements. In general, support 3 is too compliant for this particular application.

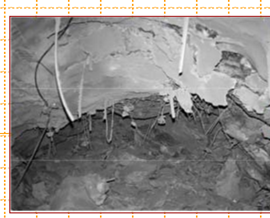
Summary: Rock Support in Yielding Rock



Brady & Brown (2006)

Support 4, of the same stiffness as support 2, is not installed until a radial displacement of the rock mass of *OG* has occurred. :

In this case, the support is installed late, excessive convergence of the excavation will occur, and the support elements will probably become overstressed before equilibrium is reached.



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