Rock Engineering Practice & Design

Lecture 12: Rock Stabilization Principles
Author's Note:

The lecture slides provided here are taken from the course “Geotechnical Engineering Practice”, which is part of the 4th year Geological Engineering program at the University of British Columbia (Vancouver, Canada). The course covers rock engineering and geotechnical design methodologies, building on those already taken by the students covering Introductory Rock Mechanics and Advanced Rock Mechanics.

Although the slides have been modified in part to add context, they of course are missing the detailed narrative that accompanies any lecture. It is also recognized that these lectures summarize, reproduce and build on the work of others for which gratitude is extended. Where possible, efforts have been made to acknowledge the various sources, with a list of references being provided at the end of each lecture.

Errors, omissions, comments, etc., can be forwarded to the author at: erik@eos.ubc.ca
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.
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 all displacements at the excavation boundary'.
✧ The second is that 'mistakes in excavation design can lead to major problems'.
Effect of Excavation on Rock Mass

In order to understand the displacements and avoid problems, we must consider the three primary effects of excavation and then decide on the ramifications for stabilizing excavations of all kinds.

The three primary effects of excavations are:

1) Displacements occur because stressed rock has been removed, allowing the remaining rock to move (due to unloading).

Hudson & Harrison (1997)
Effect of Excavation on Rock Mass

2) There are no normal or shear stresses on an unsupported excavation surface and hence the excavation boundary must be a principal stress plane with one of the principal stresses (of magnitude zero) being normal to the surface. Generally, this will involve a major perturbation of the pre-existing stress field, both in the principal stress magnitudes and their orientations.

3) At the boundary of an excavation open to the atmosphere, any previous fluid pressure existing in the rock mass will be reduced to zero (or more strictly, to atmospheric pressure). This causes the excavation to act as a 'sink', and any fluid within the rock mass will tend to flow into the excavation.
Benched excavations are used for large diameter tunnels in weak rock. The benefits are that the weak rock will be easier to control for a small opening and reinforcement can be progressively installed along the heading before benching downward. Variations may involve sequences in which the inverts, top heading and bench are excavated in different order.
**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.
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)
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)
Stabilization Strategy & Rock Mass Conditions

Rock stabilization
Maintaining the integrity of the excavation, as determined by the engineering objective.

Rock reinforcement
Bars, rods or cables are inserted into the rock mass, such that the rock mass is stiffened and strengthened, with the result that it can 'support itself'.

Continuous medium
Behaves as reinforced composite material, analogous to reinforced concrete or glass fibre reinforced plastics.

Discontinuous medium
Behaves as a continuous medium that is stiffer and stronger, because displacement on discontinuities is inhibited.

Continuous medium
Boundary conditions altered—structural elements apply forces or stresses which inhibit displacements of the continuum.

Discontinuous medium
Boundary conditions altered—structural elements apply forces or stresses inhibiting displacement of individual blocks.

Rock support
Structural elements are introduced into the excavation to inhibit rock mass displacement at the excavation boundaries, e.g. steel arches or concrete rings as used in tunnels.

Massive rock
Massive rock subjected to low in situ stress levels. No permanent support. Light support may be required for construction safety.

Massive rock
Massive rock subjected to high in situ stress levels. Pattern rockbolts or dowels with mesh or shotcrete to inhibit fracturing and to keep broken rock in place.

Jointed rock
Massive rock with relatively few discontinuities subjected to low in situ stress conditions. 'Spot' bolts located to prevent failure of individual blocks and wedges. Bolts must be tensioned.

Jointed rock
Massive rock with relatively few discontinuities subjected to high in situ stress conditions. Heavy bolts or dowels, inclined to cross rock structure, with mesh or steel fibre reinforced shotcrete on roof and sidewalls.

Heavily jointed rock
Heavily jointed rock subjected to low in situ stress conditions. Light pattern bolts with mesh and/or shotcrete will control raveling of near surface rock pieces.

Heavily jointed rock
Heavily jointed rock subjected to high in situ stress conditions. Heavy rockbolts or dowels pattern with steel fibre reinforced shotcrete. In extreme cases, steel sets with sliding joints may be required. Invert struts or concrete floor slabs may be required to control floor heave.

Hudson & Harrison (1997)

Hoek et al. (1995)
Rock Reinforcement

GRIPS, PLATES AND STRAPS AVAILABLE

CABLE BOLTS

«GARFORD BULB»
It may be thought that the use of rock reinforcement is only of use in discontinuous rock masses in order to prevent discrete block displacements. However, the use of rock reinforcement in a continuous medium can also be of benefit, especially with respect to brittle failure processes, because of the added confinement, controlling of displacements and reduction in rock mass bulking/dilation.

\[ \sigma_r = A' E' \nu \sigma_\theta \]

where \( A' \) and \( E' \) are the ratios of the cross-sectional areas and the Young’s moduli of the reinforcing element to that of the rock being reinforced, respectively, \( \nu \) is Poisson’s ratio for the rock, and \( \sigma_\theta \) is the tangential stress.

Hudson & Harrison (1997)
Rock Reinforcement in Jointed Rock

The mode of action of the reinforcement in a discontinuous medium is somewhat different, because not only are we considering improvement of the rock structure properties, but also the avoidance of large displacements of complete blocks.

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 character (quantity, length and orientation) of the reinforcement.
Rock Reinforcement in Jointed Rock

The simplest case of reinforcing a discontinuous material is that of a single block on a rock surface reinforced by a tension anchor. The tension anchor should be installed such that the block and the rock beneath act as a continuum, and block movement is inhibited.

Without the bolt, basic mechanics indicates that the block will slide if the slope angle exceeds the friction angle of the rock surface (for a cohesionless interface). This is the first criterion for indicating the potential for failure.
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 fracturing of the rock mass. Furthermore, the anchor diameter may also be determined on the basis of the tensile strength of the anchor material.
Rock Reinforcement in Jointed Rock

With respect to the bolt orientation and tension, it is not always obvious at what angle the anchor should be orientated for optimal effect. If we regard the optimal orientation as that which enables the anchor tension to be a minimum, then the angle between the anchor and the slope surface is equal to the friction angle between the block and the slope.

Hudson & Harrison (1997)
Active and Passive Reinforcement/Support

Rock reinforcement (and support) may be classified as active or passive:

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

**Passive reinforcement/support** 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.
Worked Example #1: Rock Reinforcement

Q. A circular tunnel is being excavated in a blocky rock mass by drilling and blasting. There is an Excavation Disturbed Zone (EDZ) around the excavated tunnel (defined on the basis of a blast-disturbed zone where there are loosened blocks which can fall into the tunnel under the action of gravity) which extends 0.75 m into the rock from the excavation surface.

Harrison & Hudson (2000)

i) What reinforcement pressure is required at the crown to stabilize the loose blocks of the EDZ given that the unit weight of the rock, $\gamma$, is 25 kN/m$^3$.

ii) Furthermore, if this EDZ is to be stabilized by the use of rockbolts inserted into the roof as a supporting method, and the working capacity of each bolt, $T$, is 150 kN, what area of the roof will each bolt support.
**Worked Example #1: Rock Reinforcement**

A (i). The reinforcement pressure, \( p \), can be approximated as \( W/A \), where \( W \) is the weight of the loose blocks and \( A \) is the surface area being considered.

1. Taking the EDZ volume, \( V \), above a 1 m\(^2\) area of tunnel roof, the weight of the EDZ is:

\[
W = \gamma V = 25 \times (0.75 \times 1 \times 1) = 18.75 \text{ kN}
\]

2. The area considered is \( 1 \times 1 = 1 \text{ m}^2 \), therefore the support pressure, \( p \), is:

\[
p = \frac{W}{A} = \frac{18.75 \text{ kN}}{1 \text{ m}^2} = 18.75 \text{ kPa}
\]

A (ii). If a bolt can sustain a load of 150 kN and the support pressure, \( p \), is 18.75 kPa, then:

\[
p = \frac{150 \text{ kN}}{18.75 \text{ kN/m}^2} = 8 \text{ m}^2
\]

(of roof per rockbolt)

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Harrison & Hudson (2000)
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.

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 $p_o$. 

Daemen (1977)
Rock Support Principles

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

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 \( \delta_i \) to a given value.

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

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

By Step 3: 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.
We can then plot the radial support pressure ($p_i$) required to limit the boundary displacement ($\delta_i$) to a given value.

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 \( (\delta_i) \) to a given value.

... 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 \( \delta_i \) to a given value.

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 Curve

Consider the stresses and displacements induced by excavating in a continuous, homogeneous, isotropic, linear elastic rock mass (CHILE). The radial boundary displacements around a circular tunnel assuming plane strain conditions can be calculated as:

$$u_r = \frac{R}{E}[(\sigma_1 + \sigma_2 + 2(1 - \nu^2)(\sigma_1 - \sigma_2)\cos 2\theta - \nu\sigma_3)]$$

where:
- $R$ is the radius of the opening,
- $\sigma_1$ and $\sigma_2$ are the far-field in-plane principal stresses,
- $\sigma_3$ is the far-field anti-plane stress,
- $\theta$ is indicated in the margin sketch, and
- $E$ and $\nu$ are the elastic constants.

Where the ground response curve intersects the boundary displacement axis, the $u_r$ value, represents the total deformation of the boundary of the excavation when support pressure is not provided. Typically only values less than 0.1% of the radius would be acceptable for most rock tunnelling projects.

Hudson & Harrison (1997)
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.
Worked Example #2: 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)
- \( \nu_c \) = lining Poisson ratio (assume 0.25)

Harrison & Hudson (2000)
Worked Example #2: 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. \[ u_r = \frac{pa}{2G} \quad \Rightarrow \quad u_r = \frac{(20\times 10^6 \text{Pa})(1.85 \text{m})}{2 \times (2 \times 10^9 \text{Pa})} = 0.00925 \text{m} \]

2. Plotting our ground response line, we have two known points:
   - \( p_r = 20 \text{ MPa} \), \( u_r = 0 \text{ mm} \)
   - \( p_r = 0 \text{ MPa} \), \( u_r = 9.25 \text{ mm} \)
Worked Example #2: 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:

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

Solving for the stiffness of the lining, where \( t_c = 1.85 - 1.70 = 0.15 \) m, \( E_c = 30 \) GPa and \( \nu_c = 0.25 \), we get:

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

$$k = 2.78 \text{ GPa}$$
Worked Example #2: Rock-Support Interaction

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

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

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

$$u_r = 0.014 \text{ m}$$

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

- $p_r = 20 \text{ MPa}$
  - $u_r = 0.014 \text{ mm}$

- $p_r = 0 \text{ MPa}$
  - $u_r = 1 \text{ mm}$

Operating point: $u=5.9\text{mm}$, $p=7.3\text{MPa}$
Worked Example #2: Rock-Support Interaction

Operating point:
\[ u = 5.5 \text{mm}, \ p = 8.2 \text{MPa} \]

Operating point:
\[ u = 5.9 \text{mm}, \ p = 7.3 \text{MPa} \]

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

1 mm displacement of tunnel boundary before lining is installed.
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.

Hudson & Harrison (1997)
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.

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.

Effect of excavation methods on shape of the ground response curve due induced damage and alteration of rock mass properties.
Rock Support in Highly Jointed Rock

A directly analogous ground response curve approach can be considered for the use of rock support in discontinuous rock. As the rock becomes more and more fractured with the attendant loss of strength, the ground response curve becomes progressively flatter. This effect is similar to the reduction in rock mass modulus with increasing discontinuity frequency.

The two limiting cases of the suite of ground response curves are linear elastic behaviour and zero strength. In between, it can be seen that increasingly higher support pressures are required for equilibrium with increasing discontinuity frequency.

Hudson & Harrison (1997)
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.
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.

Support 3, having a much lower stiffness, 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.
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.
Lecture References


