Learning objectives

- Develop an understanding of behaviors of rock masses near underground excavations
- Learn how to select proper support and reinforcement for underground excavations

Aspects to consider for underground excavations in rocks

Type of Underground Development	Tunnel, cavern, shaft, mine (caving and non-caving)
Excavation method	Mechanised cutting and fracturing, blasting, caving
Rock support method	Reinforcement, support, ground treatment
Life span	Long and short
Rock mechanics	Strength, deformation, abrasivity, rock mass quality, in situ stress, groundwater

Rock tunnels

- Tunnels are long linear structures for transport and utilities, generally built for long service life
- Examples include rail and metro, road and highway, canal and waterway, water transfer….

Rock caverns

- Caverns are large spans opening. They can be built on their own or part of tunnel system
- Examples include storage, warehousing and repository, powerhouse and plant, metro station, rail crossing….

Rock shafts

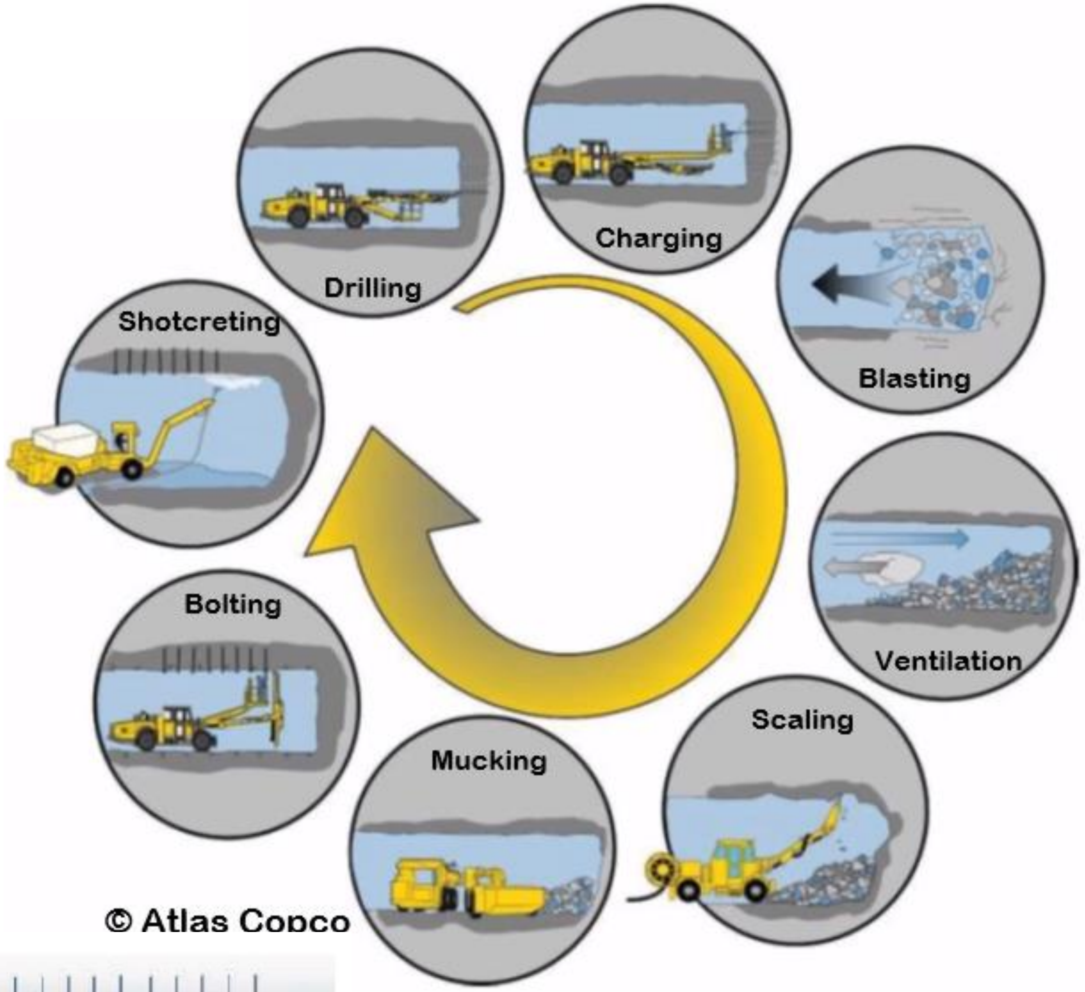
- Vertical and inclined opening to provide connections to underground development, can be permanent structure or for temporally use
- Examples include permanent access, permanent ventilation, M&E installations, construction access and transport….

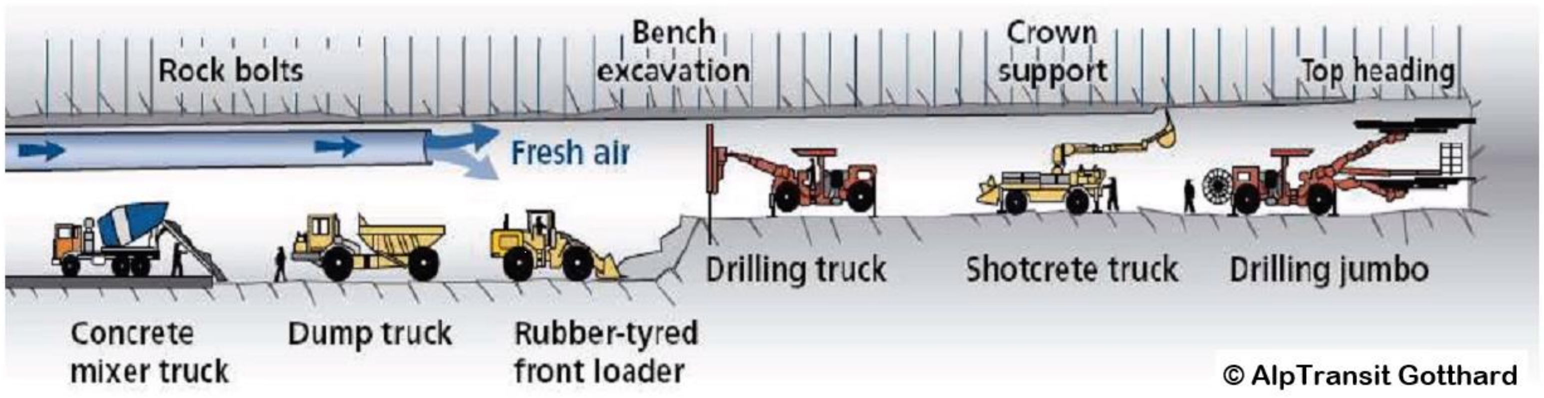
Rock excavation methods by equipment

Excavation Method	Key Characteristics
Drill-and-blasting	Primarily for hard rock, using explosives to break rocks, flexible geometry
Tunnel boring machines	For all rock, cut by roller cutters, full face and circular section.
Mobile excavators	Generally for soft and medium hard rocks, e.g., roadheader and excavator, for full face or partial face excavation.
Waterjet, chemicals, electromagnetic waves	Using high water pressure, chemical expansion or EM heating for small scale cutting or assisting machine excavation.

Drill and blast excavation

- Primarily for hard rock, using explosives to break rocks
- Excavation by blasting is flexible in terms of tunnel shape, dimension and layout





Mechanized excavation

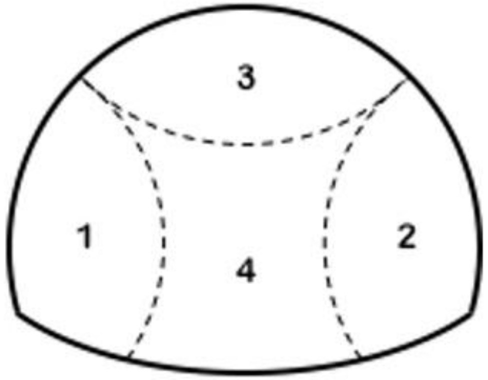
- Powerful cutting machines are developed for rock excavation
- TBM cuts all types of rocks by roller cutters, in full face and circular section
- Mobile machines (e.g. roadheader) are generally for soft and medium rocks

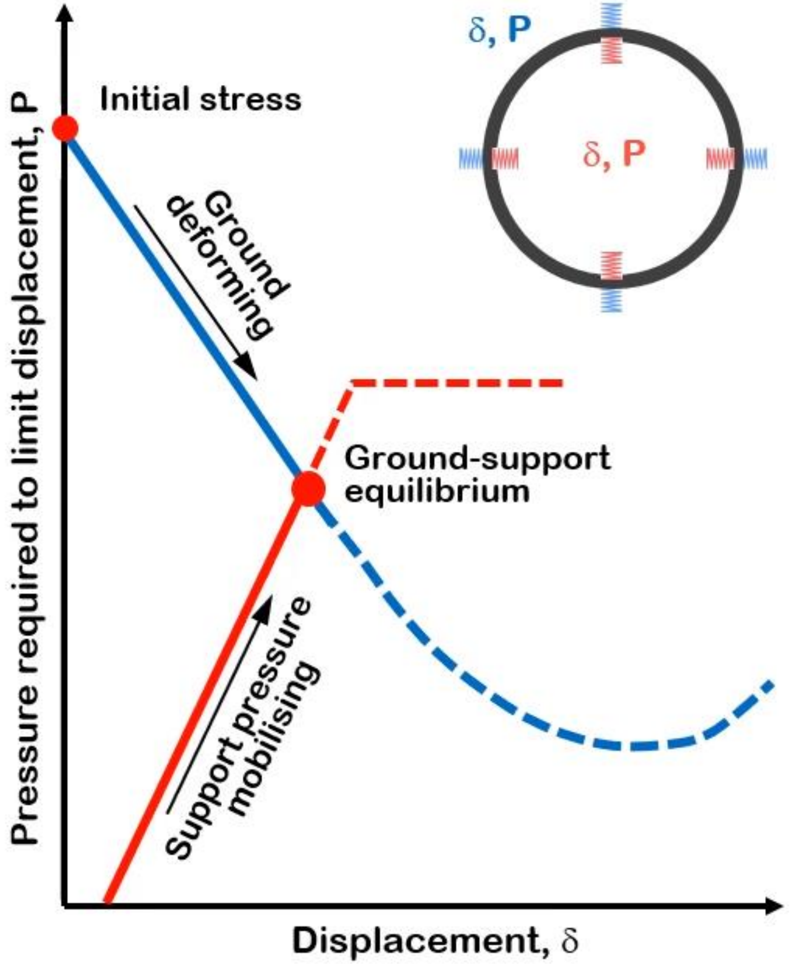
Rock excavation methods by process

Excavation Method	General Key Characteristics
Full-face excavation	For competent rocks and diameter up to 10 m, using TBM and drill-and-blast to excavate full face.
Multiple face excavation	For competent rocks with large opening size, using drill-and-blast or roadheader to excavate each faces.
Pre-conditioned full-face excavation	For highly fractured and poor rock masses, excavation zones are temporarily improved before full face excavation.
Sequential excavation (NATM)	For weak and poor rocks, face divided into sections, sequentially excavated by machine and temporally supported, internal support removed to open-up.

Sequential (NATM) excavation

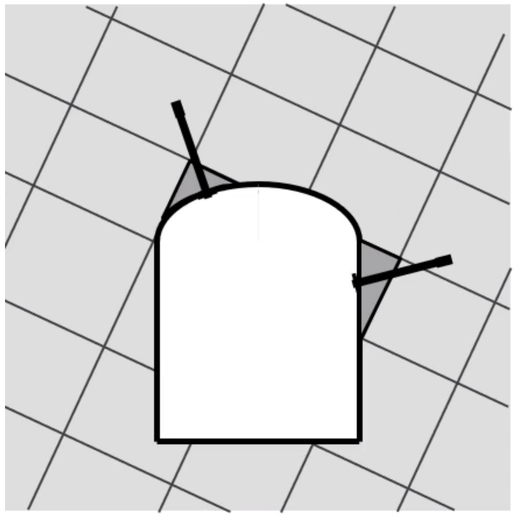
- Known as the New Austrian Tunneling Method (NATM) – primarily used in weak rocks and soils
- Is a process through small section excavation and temporary support, to form a full large opening
- Mobilize the ground to deform to release stress (by monitoring instrumentation) and then apply support





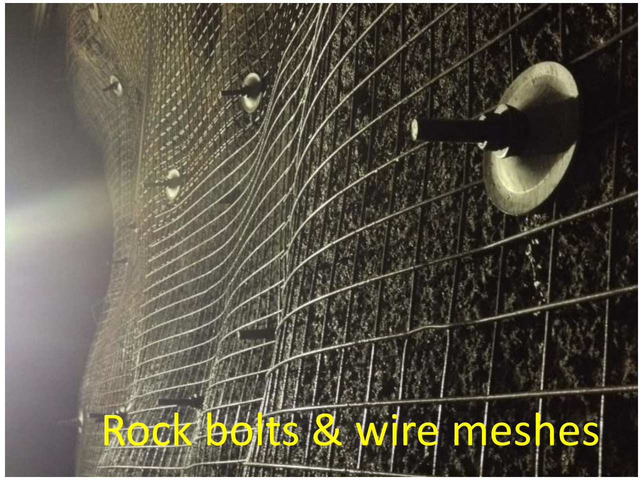
Rock reinforcement and improvement

- Rock materials are generally strong (UCS>40 MPa). Weakness is due to discontinuities
- Reinforcement is primarily to improve the continuity and the discontinuity resistance, by: bolt, anchor and cable, shotcrete, grouting, and dewatering



Rock support and protection

- Application of reactive forces to the opening, using external elements, such as pillars and lining
- Examples include: timber, concrete and steel pillars; steel sets and arch; concrete linings; wire mesh



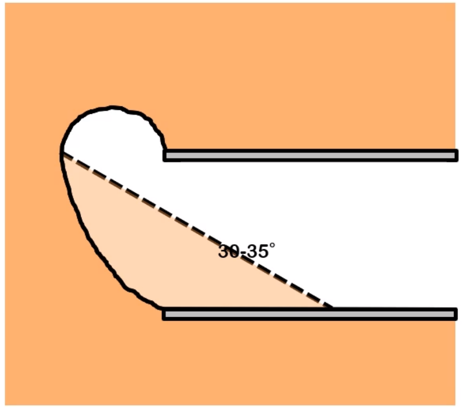
Support/reinforcement for underground excavation

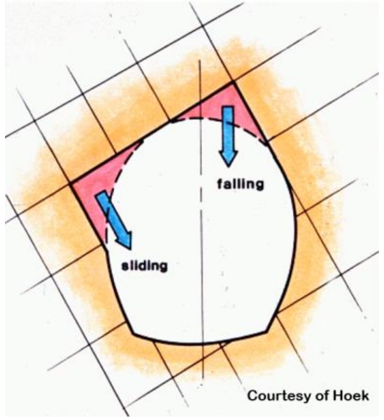
- For different failure types, different support methods should be used
- Failure types are governed by rock mass quality as well as in-situ stress

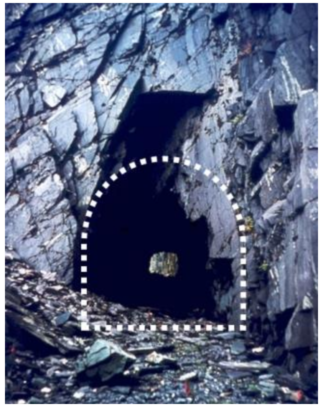
Failure Type	Support Method
Ravelling of highly fractured and weathered rock mass	Full support by concrete lining, steel sets and shotcrete
Block falling or sliding of jointed rock masses	Reinforcement by spot or system bolting, and shotcrete
Spalling and burst due to high stress	Steel sets and rock bolts for stress and wire mesh for protection
Large deformation and squeezing	Flexible steel set, yielding bolts, and concrete lining

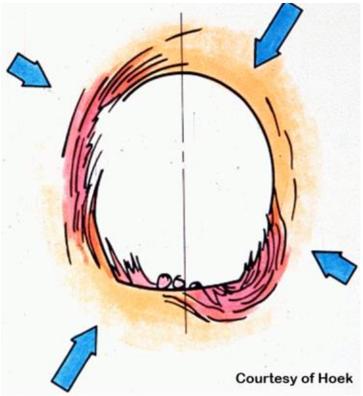
Failure types

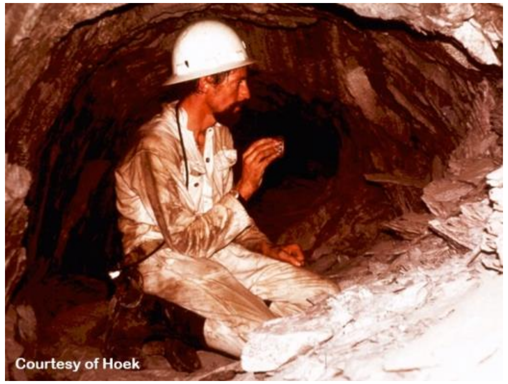
- **General failure, raveling/ running**: rock mass collapse into opening, occurs in highly fractured and weathered rock masses
- **Structurally controlled failure**: falling or sliding of rock blocks cut by joints
- **Spalling/rock burst**: layers/pieces of rocks detached under highly stressed good-quality brittle rock
- **Squeezing**: large deformation failure of weak rock under high stresses

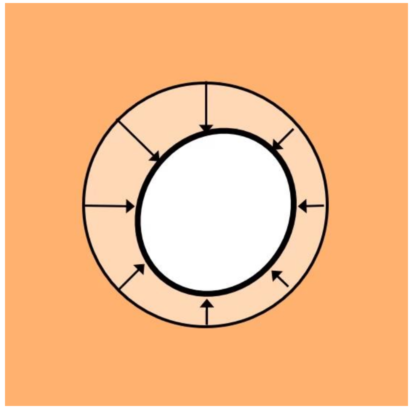










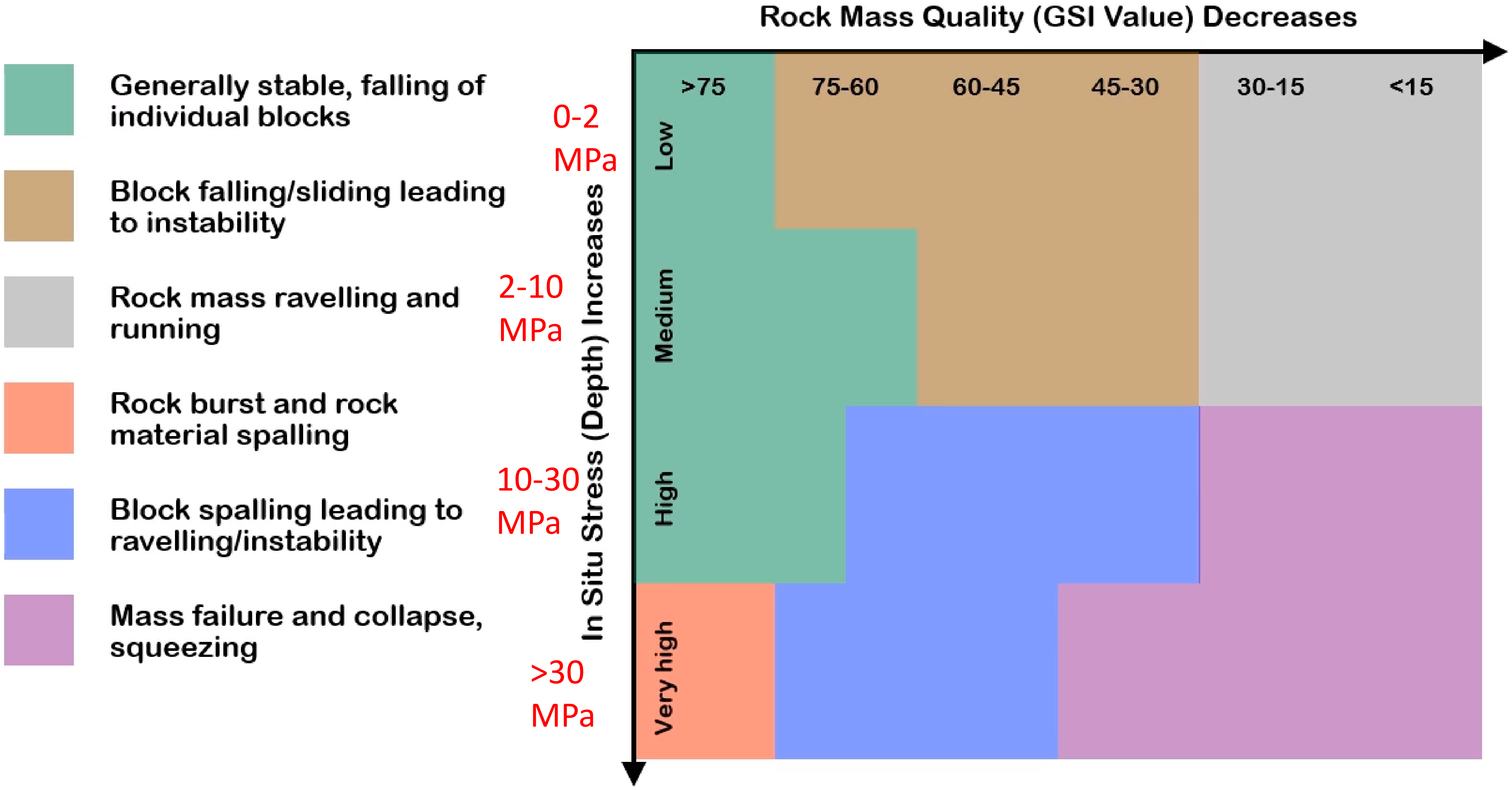


Failure types for various GSI and in-situ stress

Rock mass quality decreases →

Stress increases ↓

	Blocky and strong rock	Poor and weak rock
Low stress	Structural failure	General failure
High stress	Stress failure	Squeezing failure



Rock support design method

Rock Quality and Failure Type	Support Design Method
Jointed competent rock masses, block failure	Rock mass classifications (Q and RMR), rock joint assessment
Highly fractured and poor rock, general failure	Ground pressure, rock mass classifications
High in situ stress, burst and spalling	Stress analysis, shape optimisation
Squeezing and swelling rock masses, large deformation	Ground pressure and displacement analysis Sequential (NATM) excavation

Support Design using Q-System

$$Q = \frac{RQD}{J_n} \frac{J_r}{J_a} \frac{J_w}{SRF}$$

- When Barton developed the Q system for rock mass classification, his ultimate aim was to predict the appropriate support to be used in tunnels

Q-Value	Rock Mass Quality
400 ~ 1000	Exceptionally Good
100 ~ 400	Extremely Good
40 ~ 100	Very Good
10 ~ 40	Good
4 ~ 10	Fair
1 ~ 4	Poor
0.1 ~ 1	Very Poor
0.01 ~ 0.1	Extremely Poor
0.001 ~ 0.01	Exceptionally Poor

Support Design using Q-System

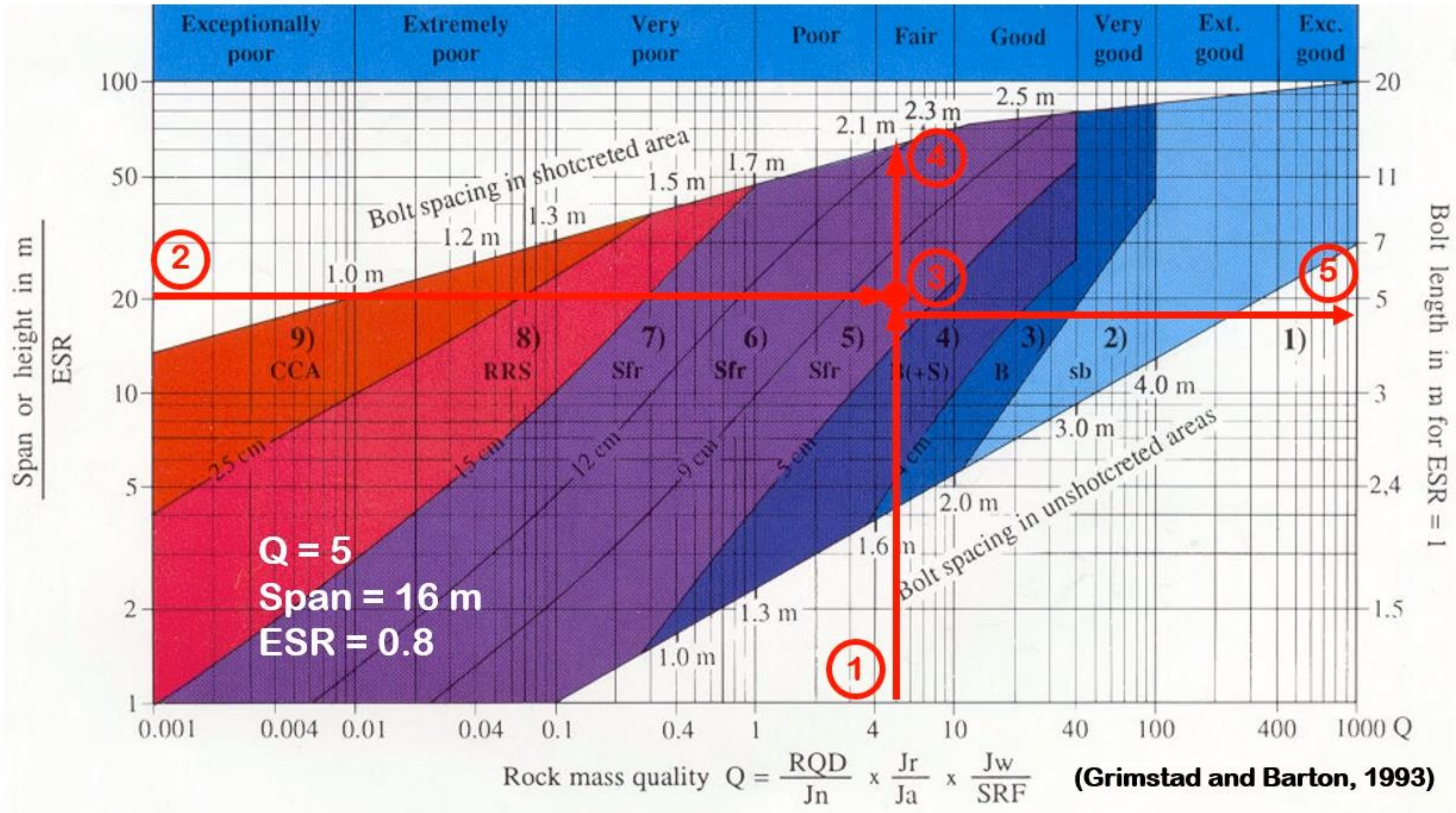
- Tunnel stability is related rock mass quality and opening size, and tunnel safety requirement/usage
- To relate *Q* to the behaviour and support requirements in underground excavations, Barton defined the equivalent dimension, *De*, of the excavation
- *De* is obtained by dividing the span, diameter, or wall height of the excavation by the excavation support ratio, *ESR*, which is roughly analogous to the inverse of the factor of safety

$$De = \frac{\text{Actual excavation span or height}}{\text{Excavation support ratio, ESR}}$$

Excavation support ratio, *ESR*

Excavation Category	ESR
Temporary mine openings.	3–5
Permanent mine openings, water tunnels for hydro-electric projects, pilot tunnels, drifts and headings for large excavations.	1.6
Storage rooms, water treatment plants, minor road and railway tunnels, surge chambers and access tunnels in hydro-electric project.	1.3
Underground power station caverns, major road and railway tunnels, civil defence chamber, tunnel portals and intersections.	1.0
Underground nuclear power stations, railway stations, sports and public facilities, underground factories.	0.8

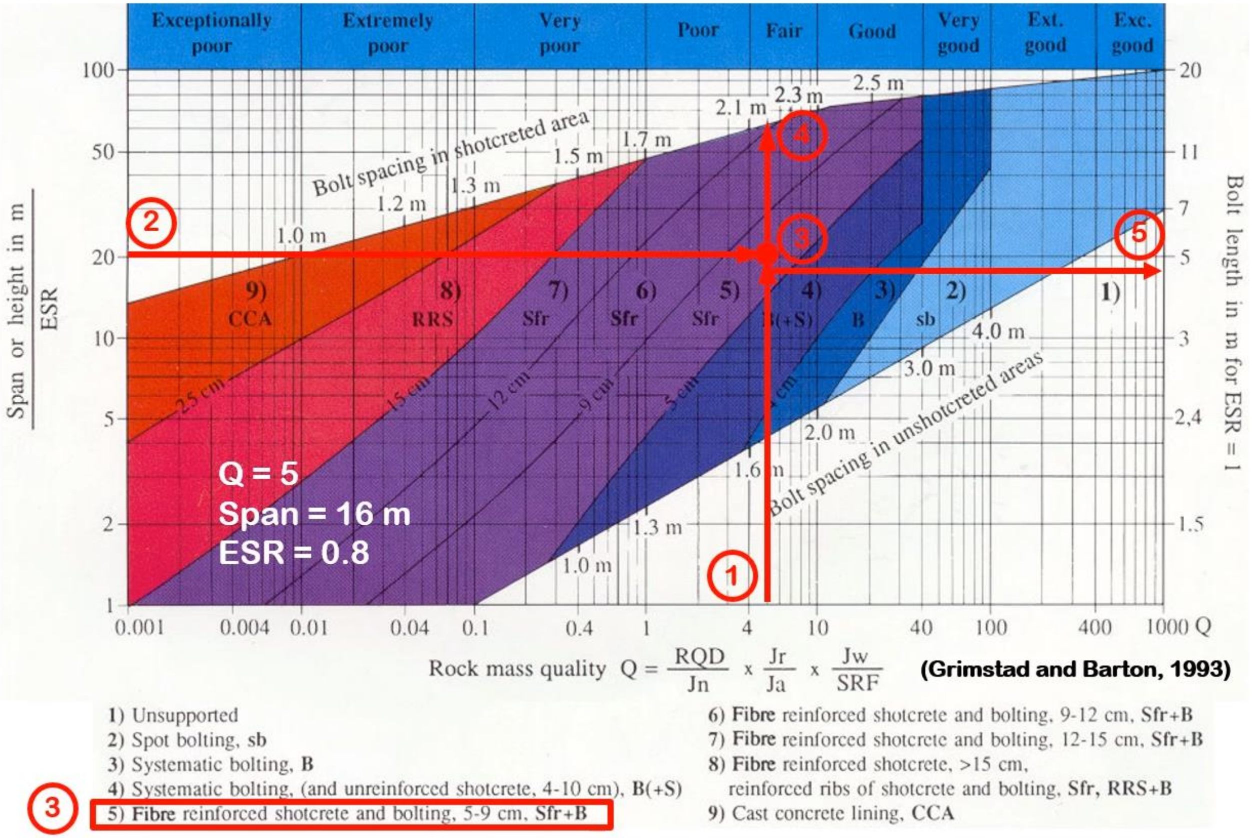
Support design using Q-system



1) Unsupported
2) Spot bolting, sb
3) Systematic bolting, B
4) Systematic bolting, (and unreinforced shotcrete, 4-10 cm), B(+S)
3 — 5) Fibre reinforced shotcrete and bolting, 5-9 cm, Sfr+B
6) Fibre reinforced shotcrete and bolting, 9-12 cm, Sfr+B
7) Fibre reinforced shotcrete and bolting, 12-15 cm, Sfr+B
8) Fibre reinforced shotcrete, >15 cm, reinforced ribs of shotcrete and bolting, Sfr, RRS+B
9) Cast concrete lining, CCA

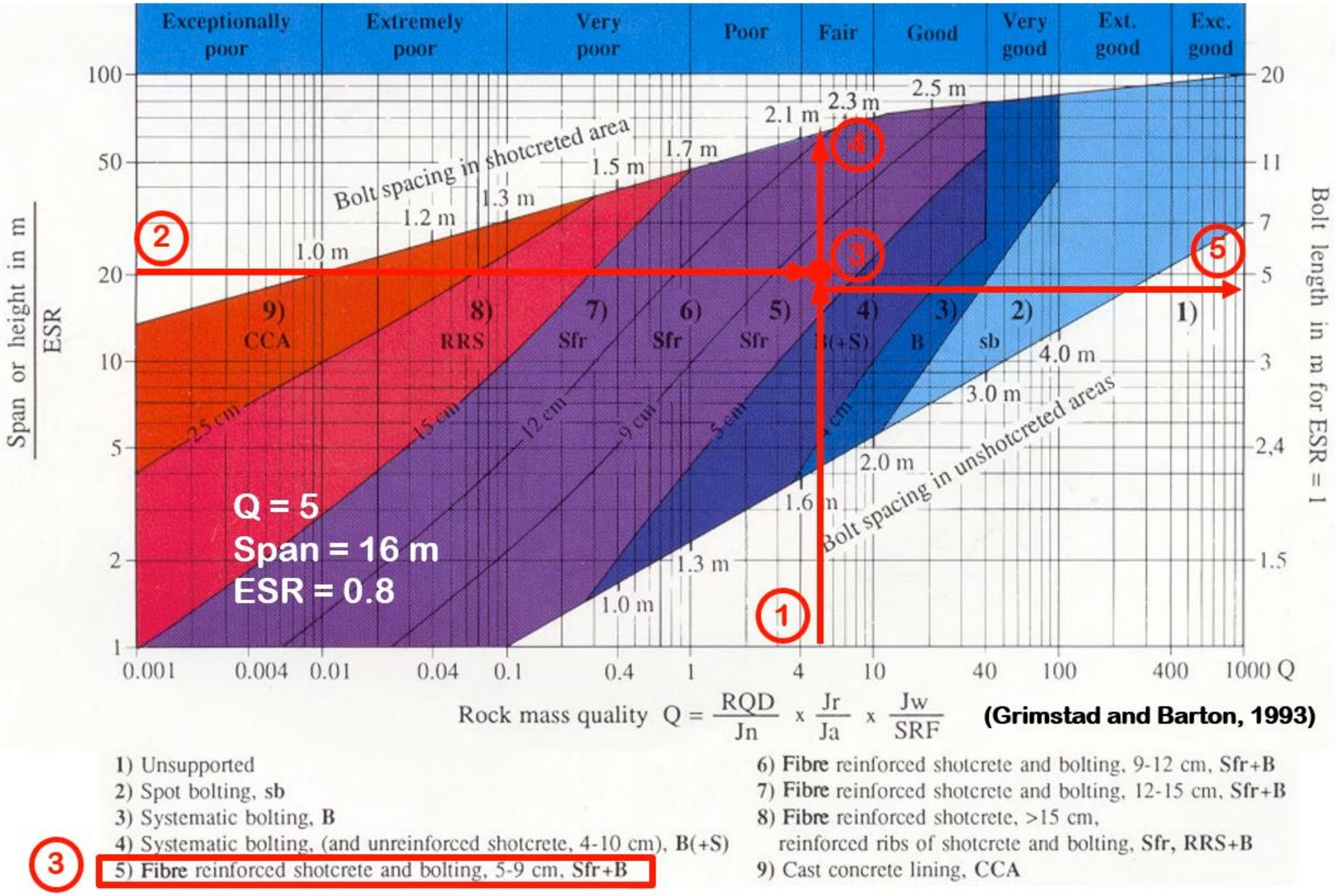
Support design using Q-system

1. Horizontal axis is the surrounding rock mass Q value
2. Left axis is the tunnel equivalent span (span/ESR)
3. Intersection point defines support category, and gives shotcrete thickness
4. Vertical up from the intersection gives bolt spacing in shotcreted area. Vertical down gives bolt spacing in unshotcreted area (not recommended for roof)
5. Horizontal to the right using the actual span (ESR=1) gives bolt length



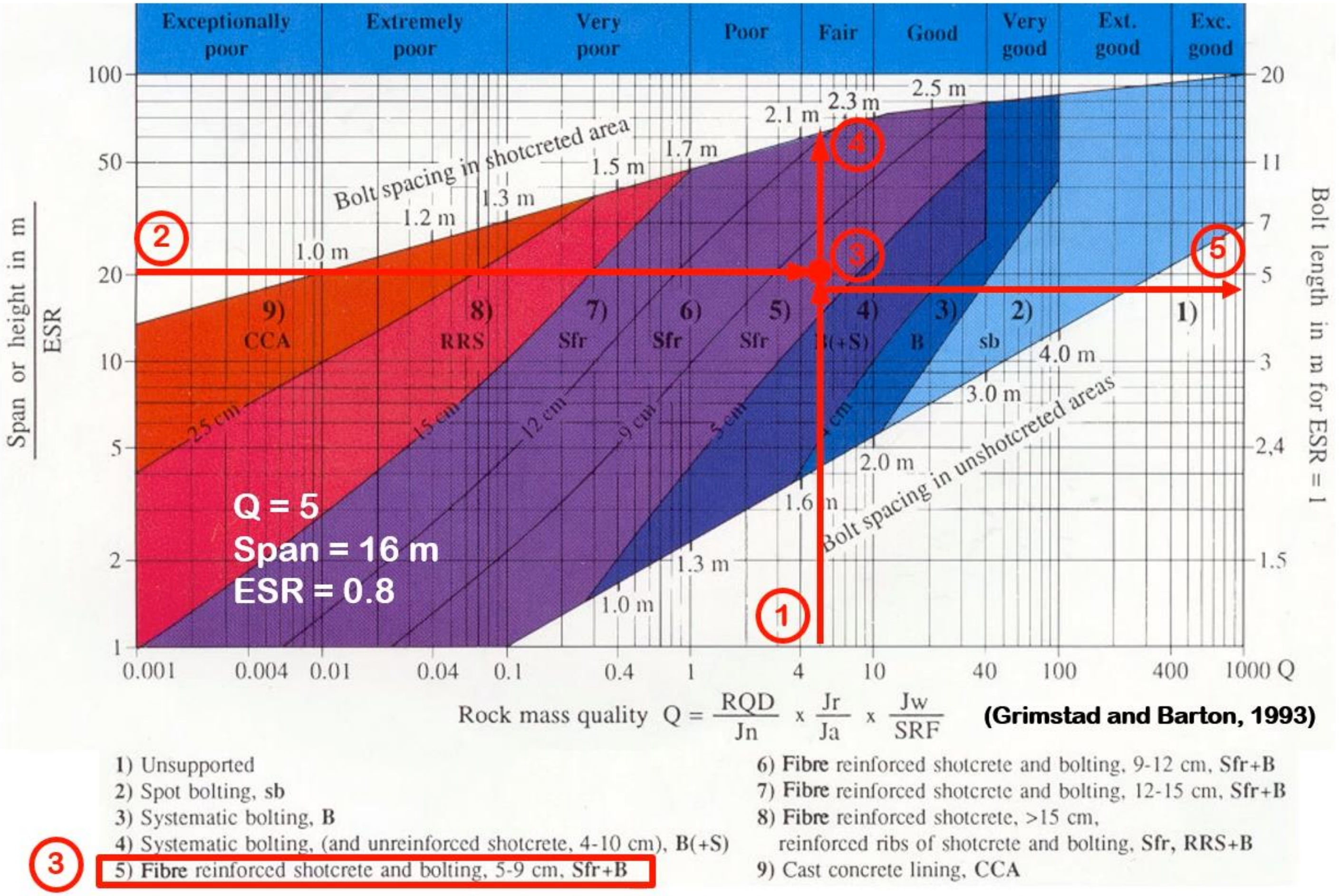
Influence of ESR and safety requirement

- Bolt length is determined based on the actual span or height, not affected by ESR
- Bolt spacing is determined by Q-value, and is not affected by ESR
- In support Zone (2) to (7), ESR effectively changes shotcrete thickness
- Left axis is the tunnel equivalent span (span/ESR)
- Safety is improved by increasing shotcrete thickness, protecting small block from falling



Spot bolt length and spacing

- Spot bolting (category 2) is to secure individual rock blocks potentially unstable. The location of bolt is where the unstable block and wedge are
- Bolt length should be sufficient to obtain adequate anchorage in the stable rocks beyond the bolted blocks (1-2 m into stable rocks)
- The size of unstable rock blocks can be estimated from joint spacing and orientation observation



Design of wall support

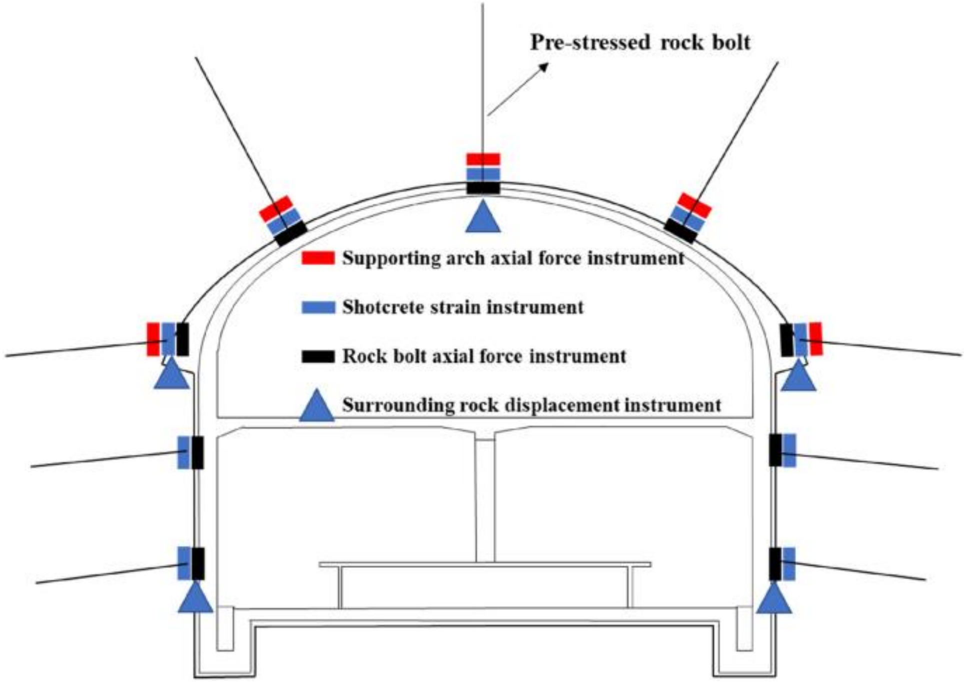
- Previous slides are for the roof of tunnels
- For walls, typically less support is needed
- Following adjustment to Q can be used

For $Q > 10$, $Q_{wall} = 5\,Q$

For $0.1 < Q < 10$, $Q_{wall} = 2.5\,Q$

For $Q < 0.1$, $Q_{wall} = Q$

- Wall height should also use ESR to get equivalent height for support design

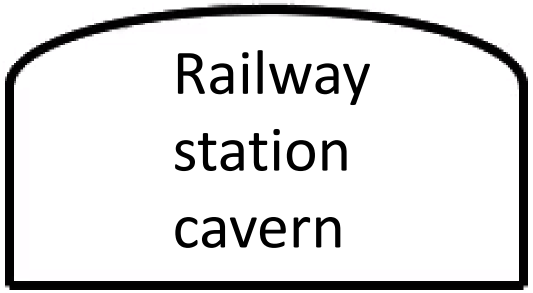


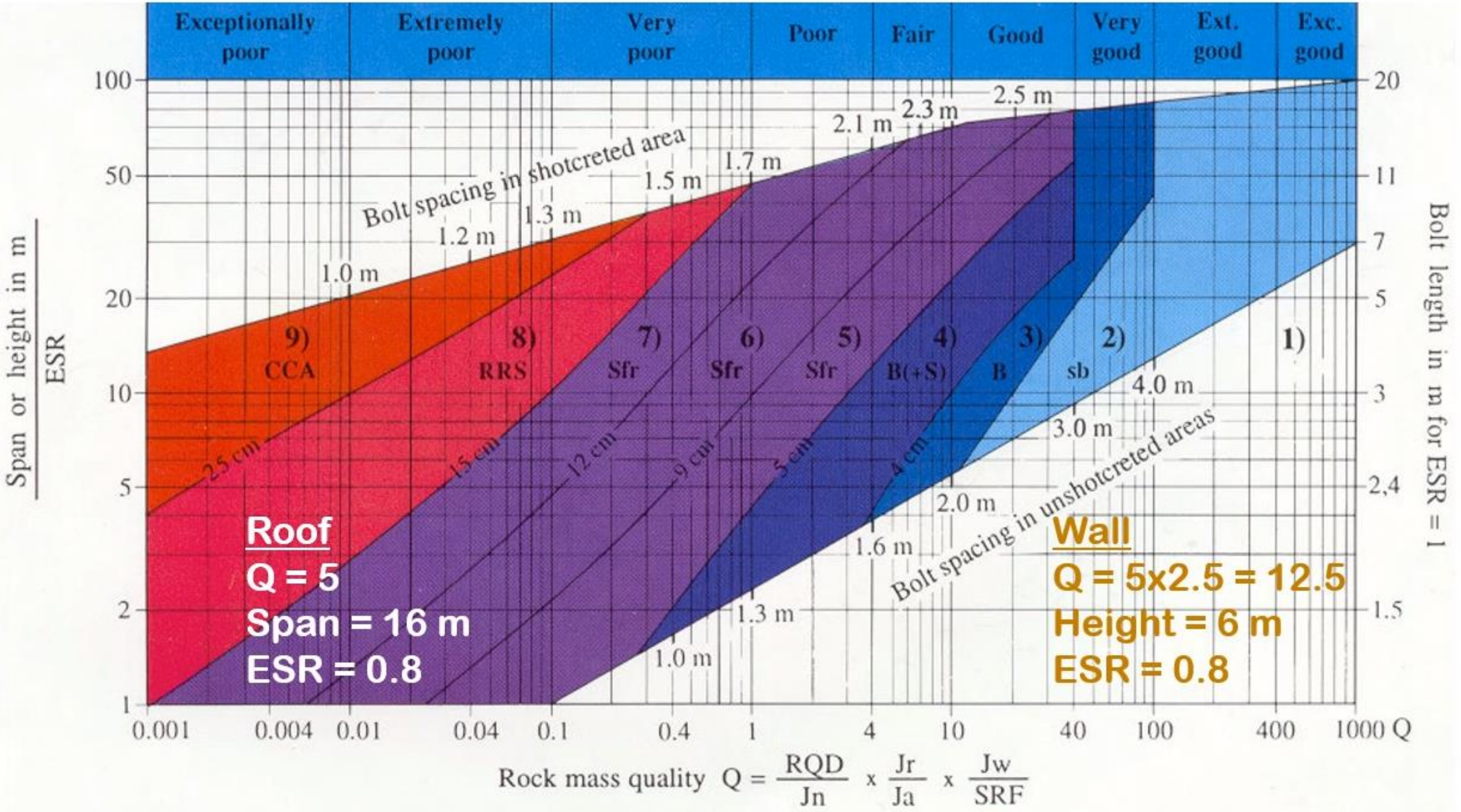
Example

- Railway station cavern, span 16 m, wall height 6 m, Q = 5 (fair)

- Roof: ESR = 0.8, De=16/0.8 m
- Support: Category 5, fibre-reinforced shotcrete of 8 cm, bolt spacing at 2.2 m, bolt length of 4.5 m

- Wall: ESR = 0.8, De=6/0.8 m, Q_{wall}= 2.5 Q = 12.5
- Support: Category 3, bolt spacing at 2.4 m, bolt length of 2.5 m, no shotcrete





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7) **Fibre** reinforced shotcrete and bolting, 12-15 cm, **Sfr+B**
8) **Fibre** reinforced shotcrete, >15 cm, reinforced ribs of shotcrete and bolting, **Sfr, RRS+B**
9) Cast concrete lining, **CCA**

Comments on Q-system for support design

- Q-system is best for competent rocks with rock mass quality of poor and above (Q>1)
- For support categories 2 and 3, a thin layer of shotcrete at roof is highly recommended
- For excavation of very large span of more than 20 m, in situ horizontal stress perpendicular to tunnel axis should be taken into design consideration

Support Design using RMR

- RMR is a measure of rock mass quality, as well as a measure of rock mass stability in relation to opening size
- It was initially developed to estimate stand-up time for mines of various opening size in rocks of various quality

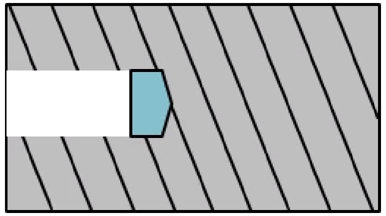
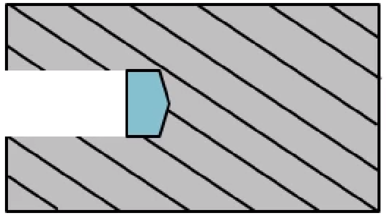
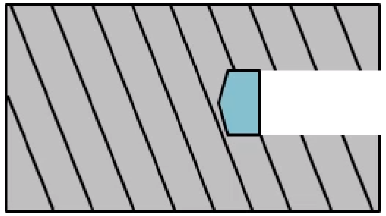
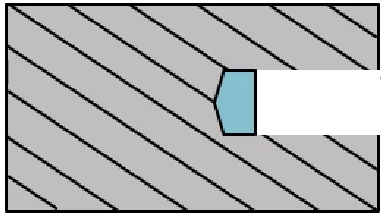
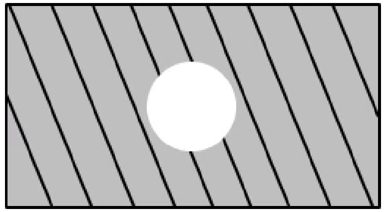
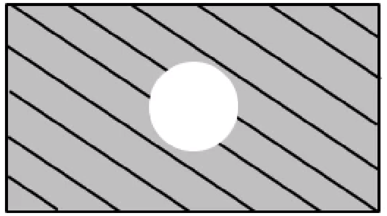
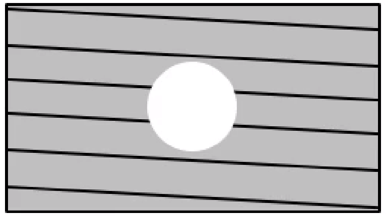
$$\text{Basic RMR} = R_{\sigma} + R_{RQD} + R_{js} + R_{jc} + R_{gw}$$

(a) Basic RMR Rating (Bieniawski 1989)					
Basic RMR rating is the sum of ratings of five rock parameters: (i) rock material strength, (ii) RQD, (iii) joint spacing, (iv) joint condition and, (v) groundwater condition.					
RMR ratings	>81	61 – 80	41 – 60	21 – 40	< 20
Rock mass quality	Very good	Good	Fair	Poor	Very poor
Average stand-up time	10 year for 15 m span	6 months for 8 m span	1 week for 5 m span	10 hours for 2.5 m span	30 minutes for 0.5 m span

Basic RMR and rating adjustment

- To use RMR for tunnel support design, RMR rating needs to be adjusted for tunnel alignment with respect to joint orientations of each joint set

Adjusted RMR = Original RMR + Adjustment

Condition defined by the effects of joint orientation in tunnelling			
Joint strike ⊥ to tunnel axis, drive with dip		Joint strike ⊥ to tunnel axis, drive against dip	
Dip angle 45° – 90° Very favourable (0) 	Dip angle 20° – 45° Favourable (–2) 	Dip angle 45° – 90° Fair (–5) 	Dip angle 20° – 45° Unfavourable (–10) 
Joint strike // to tunnel axis		Sub-horizontal joint (Dip angle 0° – 20°)	
Dip angle 45° – 90° Very unfavourable (–12) 	Dip angle 20° – 45° Fair (–5) 	Irrespective of strike Fair (–5) 	

RMR rock support design guide

Adjusted RMR ratings	Original RMR ratings (Laubscher and Taylor 1976)								
	>80	70-80	60-70	50-60	40-50	30-40	20-30	10-20	0-10
>50	a	a	a	a					
40-50		b	b	b	b				
30-40			c, d	c, d	c, d, e	d, e			
20-30				g	f, g	f, g, j	f, h, j		
10-20					i	i	h, i, j	h, j	
0-10						k	k	l	l

Explanations on RMR design guide

a. Generally no support, but joint intersections may require local bolting.	b. Patterned, grouted bolts at 1.0 m spacing.
c. Patterned, grouted bolts at 0.75 m spacing.	d. Patterned, grouted bolts at 1.0 m spacing, and shotcrete 100 mm thick.
e. Patterned, grouted bolts at 1.0 m spacing, and massive concrete 300 mm thick; only used if stress changes are not excessive.	f. Patterned, grouted bolts at 0.75 m spacing, and shotcrete 100 mm thick.
g. Patterned, grouted bolts at 0.75 m spacing, and mesh-reinforced shotcrete 100 mm thick.	h. Patterned, grouted bolts at 1.0 m spacing, and massive concrete 450 mm thick; if stress changes are not excessive.
i. Patterned, grouted bolts at 0.75 m spacing, and mesh-reinforced shotcrete 100 mm thick, plus yielding steel arches as repair technique if stress changes are excessive.	j. Stabilize with wire-mesh cover support and massive concrete 450 mm thick; if stress changes are not excessive.
k. Stabilize with wire-mesh cover support followed by 100-150 mm shotcrete (including face if necessary), plus yielding steel arches where stress changes excessive.	l. Avoid failure development in this ground if possible; otherwise, use support systems j or k. (Laubscher and Taylor 1976)

Notes on RMR design guide

1.	The original RMR rating, as well as the adjusted ratings, must be considered in assessing ground-support requirements.
2.	Rock bolts are generally ineffective in highly jointed rock masses and should not be used as the sole support when the joint spacing rating is less than 6.
3.	Support recommendations in the table are applicable to mine openings with stress levels less than 30 MPa.
4.	Large chambers should only be excavated in rock with adjusted total RMR of 50 or better.

(Hoek and Brown 1980)

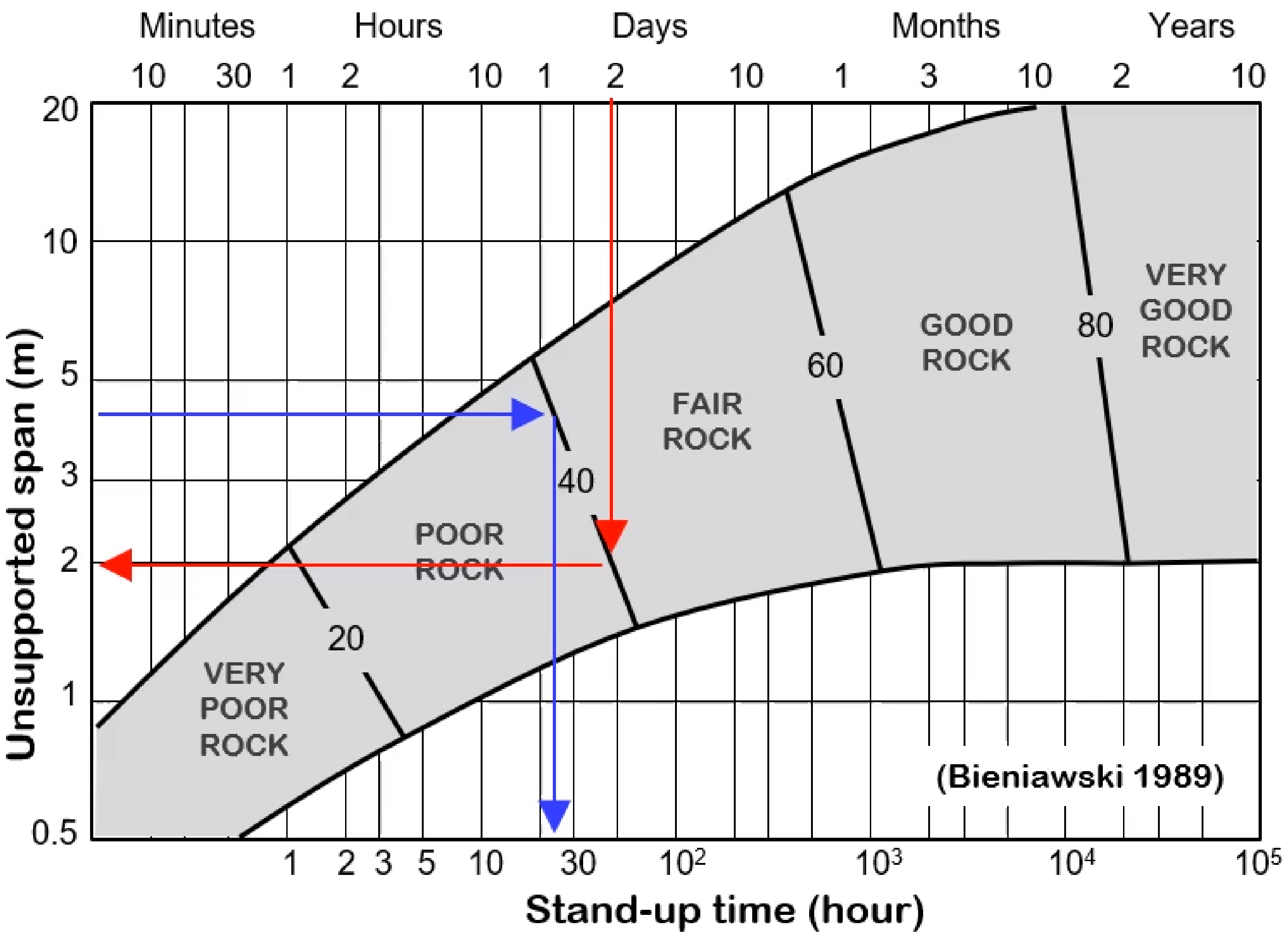
Guide on bolt length/spacing and shotcrete

Bolt Length	Bolt Spacing	Shotcrete
• > 2 x bolt spacing • > 3 x average joint spacing • 0.5B, for spans B<6m • 0.25B, for spans B>18m • >0.2H, for wall H>18m	• < 0.5 x bolt length • < 1.5 x average joint spacing • < 2 m if to anchor wire mesh	• Shotcrete thickness should not exceed 20cm. • Thick layers of shotcrete may be applied occasionally to small areas of particularly poor rock.

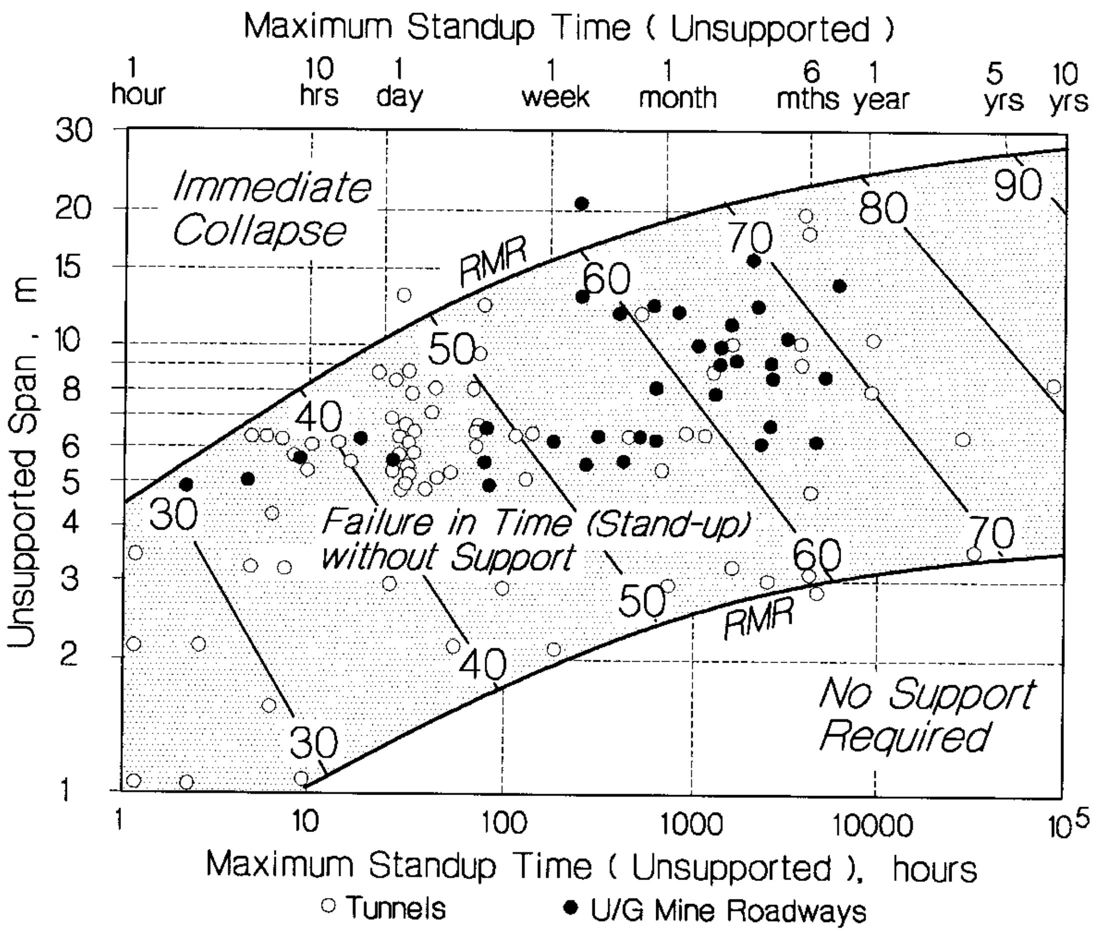
- Rock bolt design for major zones of instability (seams, fault and shear zones) should be the subject of stability analysis
- Systematic bolting with fiber reinforced shotcrete should be used for roof support for tunnels occupied by people or used as important facilities

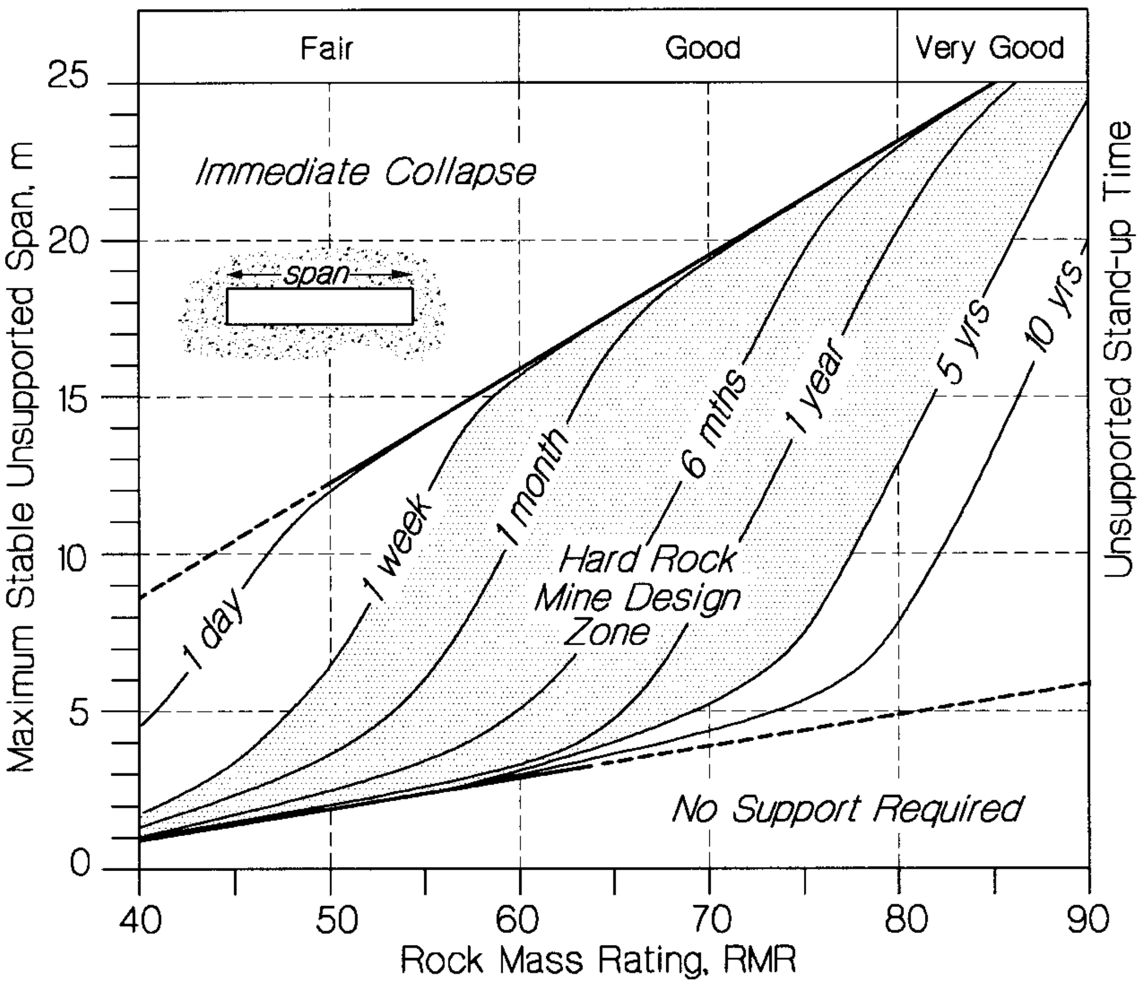
Estimation of maximum unsupported span/stand-up time

- Using RMR, maximum unsupported span can be estimated from stand-up time, and vice versa

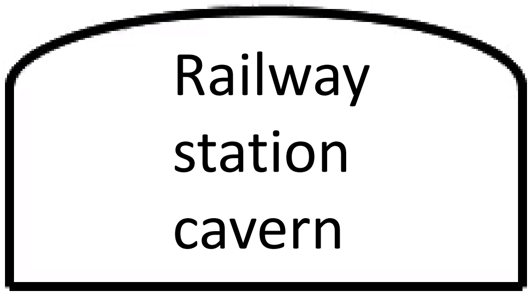


Estimation of maximum unsupported span/stand-up time





Example



- Railway station cavern, span 16 m, wall height 6 m
- RMR = 50 (fair)
- Two joint sets: (1) strike normal to tunnel axis dipping at 30°, drive with dip, (2) strike parallel to tunnel axis dipping at 70°

- Adjustment for joint orientation: (1) unfavorable against or favorable (with), (2) very unfavorable
- Adjustment = (-2) + (-12)= -14; adjusted RMR = 36;
- Support: patterned grouted bolts at 1.0 m spacing, shotcrete 100 mm thick, bolt length 4-5 m. Fiber reinforced shotcrete

Adjusted RMR ratings	Original RMR ratings								
	>80	70-80	60-70	50-60	40-50	30-40	20-30	10-20	0-10
>50	a	a	a	a					
40-50		b	b	b	b				
30-40			c, d	c, d	c, d, e	d, e			
20-30				g	f, g	f, g, j	f, h, j		
10-20					i	i	h, i, j	h, j	
0-10						k	k	l	l

d: Patterned grouted bolts at 1.0 m spacing, shotcrete 100 mm thick.

Bolt length = (0.25-0.3)B = 4-5 m. Fibre reinforced shotcrete with human occupancy.

Comments on RMR support design

- Estimation of unsupported span and stand-up time is useful for underground excavation
- Support design is primarily for tunnels of small to medium (3-10) size
- Design does not sufficiently address the size variations
- Design does not consider the usage and safety requirements

Rock support design method

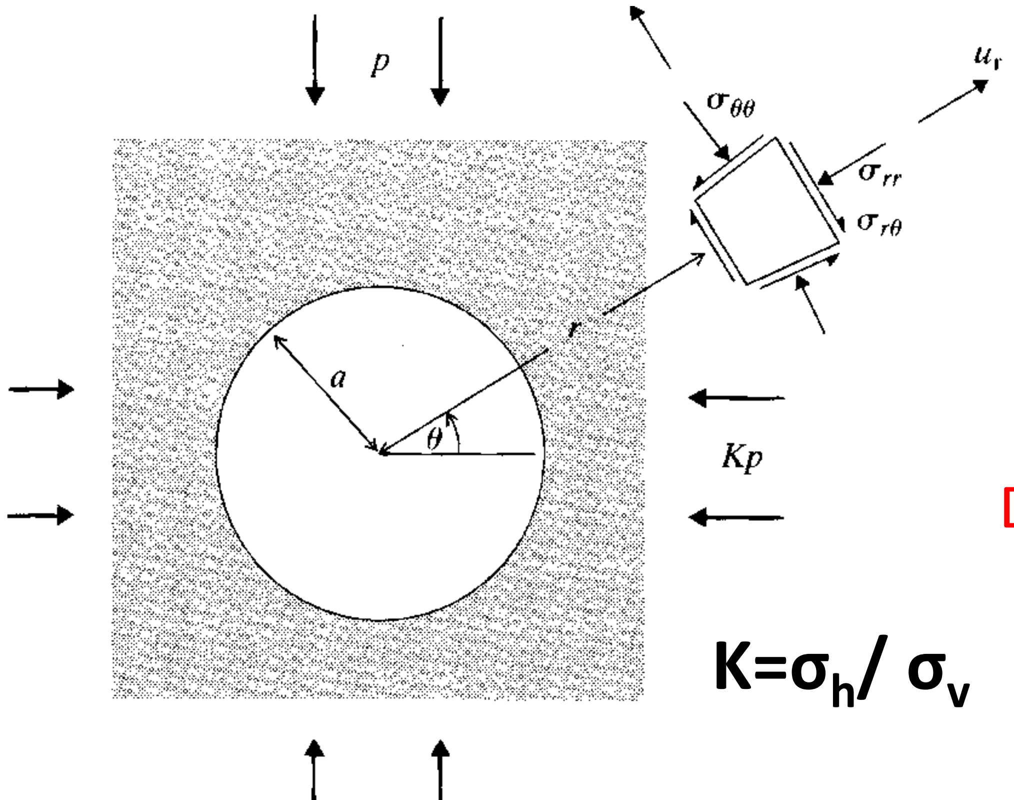
Rock Quality and Failure Type	Support Design Method
Jointed competent rock masses, block failure	Rock mass classifications (Q and RMR), rock joint assessment
Highly fractured and poor rock, general failure	Ground pressure, rock mass classifications
High in situ stress, burst and spalling	Stress analysis, shape optimisation
Squeezing and swelling rock masses, large deformation	Ground pressure and displacement analysis Sequential (NATM) excavation

Stress-controlled instability mechanisms

- Stresses of rock masses around an underground excavation is complex (discontinuous, inhomogeneous, anisotropic, non-elastic)
- Initially can be simplified using CHILE (continuous, homogenous, isotropic, linear elastic)
- Many CHILE analysis has been useful in excavation at depth where high stresses have closed fractures and rock mass is relatively homogenous and isotropic
- In near surface excavation, CHILE typically has large errors (low stress, highly fracture/weathering)

Kirsch equations

- Exact theoretical solution for the elastic stress distribution around a singular circular opening in a CHILE material
- Stresses at the wall are independent of the opening size (a=r)
- Deformations depend on elastic constants and the opening size



$K = \sigma_h / \sigma_v$

Stresses

$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right) - (1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right) + (1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{r\theta} = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

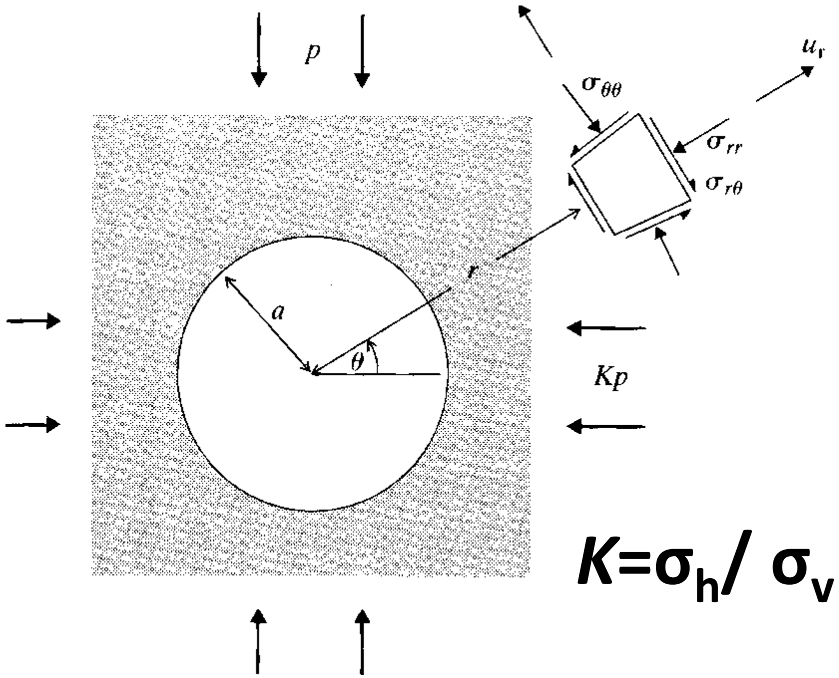
Deformations

$$u_r = -\frac{pa^2}{4Gr}\left[(1+K) - (1-K)\left(4(1-\upsilon) - \frac{a^2}{r^2}\right)\cos 2\theta\right]$$

$$u_\theta = -\frac{pa^2}{4Gr}\left[(1-K)\left(2(1-2\upsilon) + \frac{a^2}{r^2}\right)\sin 2\theta\right]$$

Stress around the circular boundary

- When r = a, the boundary stresses given by Kirsch equation:



$K=\sigma_h/\sigma_v$

$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right)-(1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$ = 0

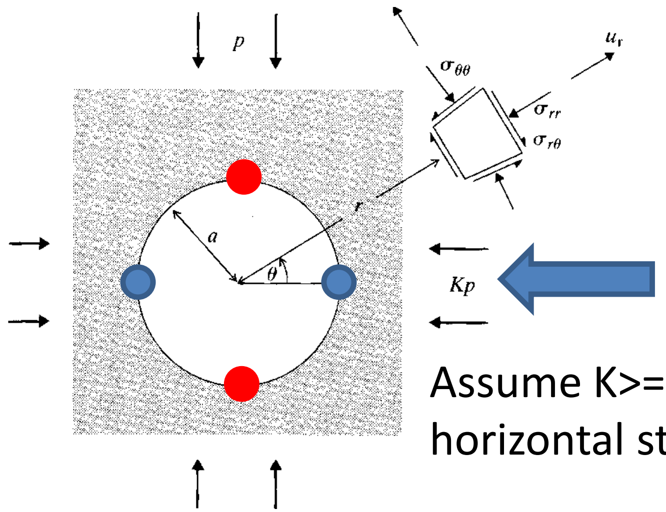
$$\sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right)+(1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$ = p[(1+k)+2(1-k)cos2θ]

$$\sigma_{r\theta} = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$ = 0

- Radial stresses are zero for no internal pressure
- Shear stresses must be zero for no shear along the circular boundary

Maximum and minimum tangential boundary stresses

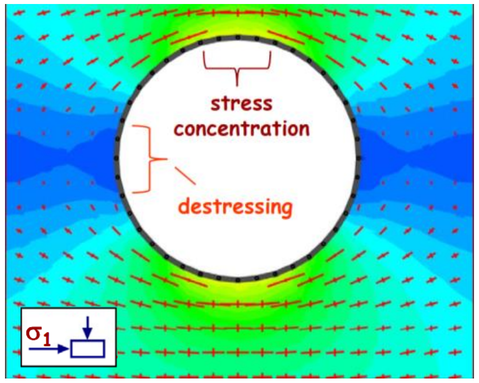
- *Maximum* and *minimum* boundary stresses can be compared with the compressive and tensile strengths of the rock to assess the likelihood of rock fracturing/potential excavation failure

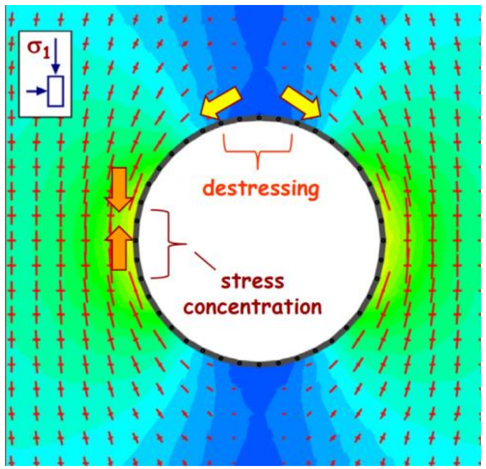


Assume K>=1, maximum horizontal stress

$\sigma_{\theta\theta}$ = p[(1+k)+2(1-k)cos2θ]

- $\sigma_{\theta \min} = 3\sigma_{H \min} - \sigma_{H \max}$
- $\sigma_{\theta \max} = 3\sigma_{H \max} - \sigma_{H \min}$

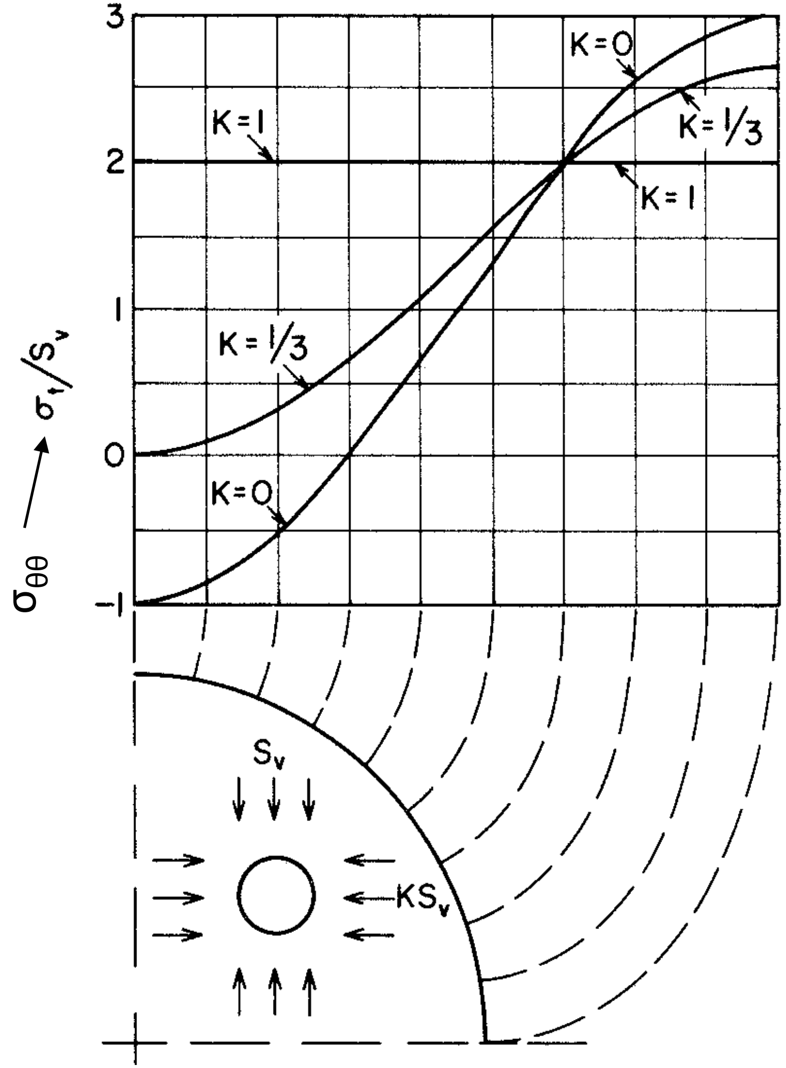




- If K=1, $\sigma_{H \max} = \sigma_{H \min} = p$ $\quad \sigma_{\theta \min} = \sigma_{\theta \max} = 3p - p = 2p$
- If K=2, $\sigma_{H \max} = 2p \quad \sigma_{H \min} = p$ $\quad \sigma_{\theta \min} = 3\sigma_{H \min} - \sigma_{H \max} = p$

$$\sigma_{\theta \max} = 3\sigma_{H \max} - \sigma_{H \min} = 5p$$

Tangential stresses $\sigma_{\theta\theta}$ around a tunnel boundary



$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right)-(1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right)+(1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{r\theta} = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

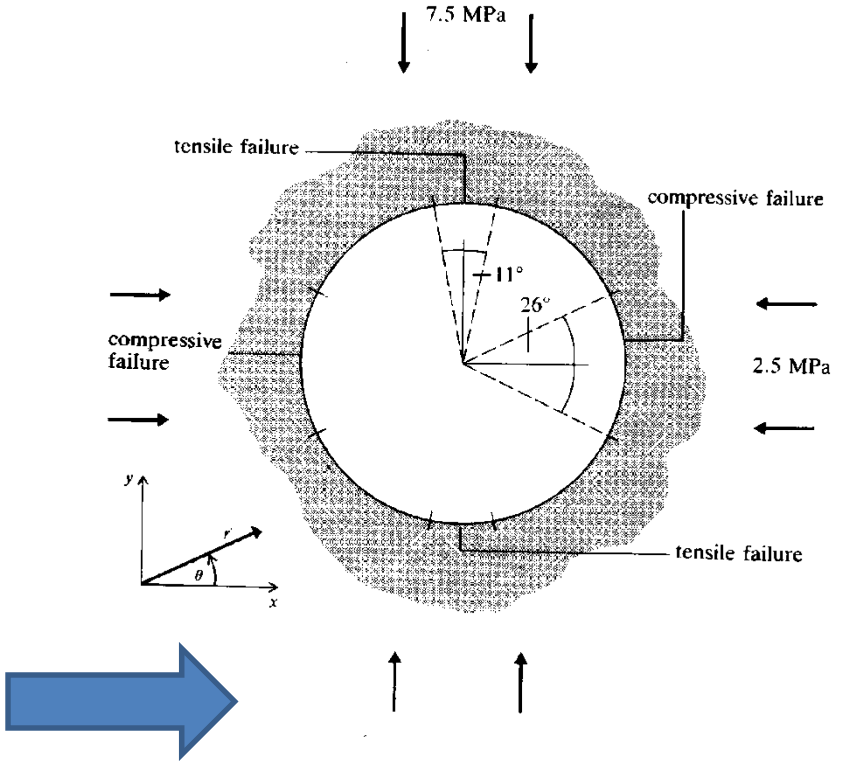
If K=1, θ = 0, 45, 90……

If K=0, θ = 0, 45, 90……

Zones of rock failure

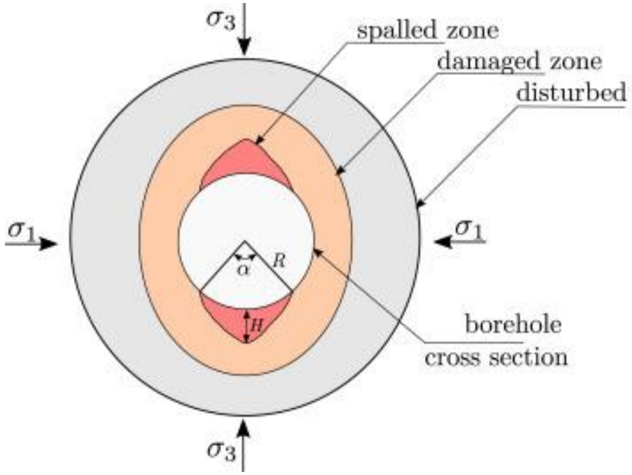
- Compare elastic stresses with an appropriate Hoek-Brown failure criterion to determine location and extent of failure zones
- If the compressive strength is 16 MPa and the tensile strength is 0 MPa, then can determine the locations…
- Where around the boundary for the case on the right would be damaged?

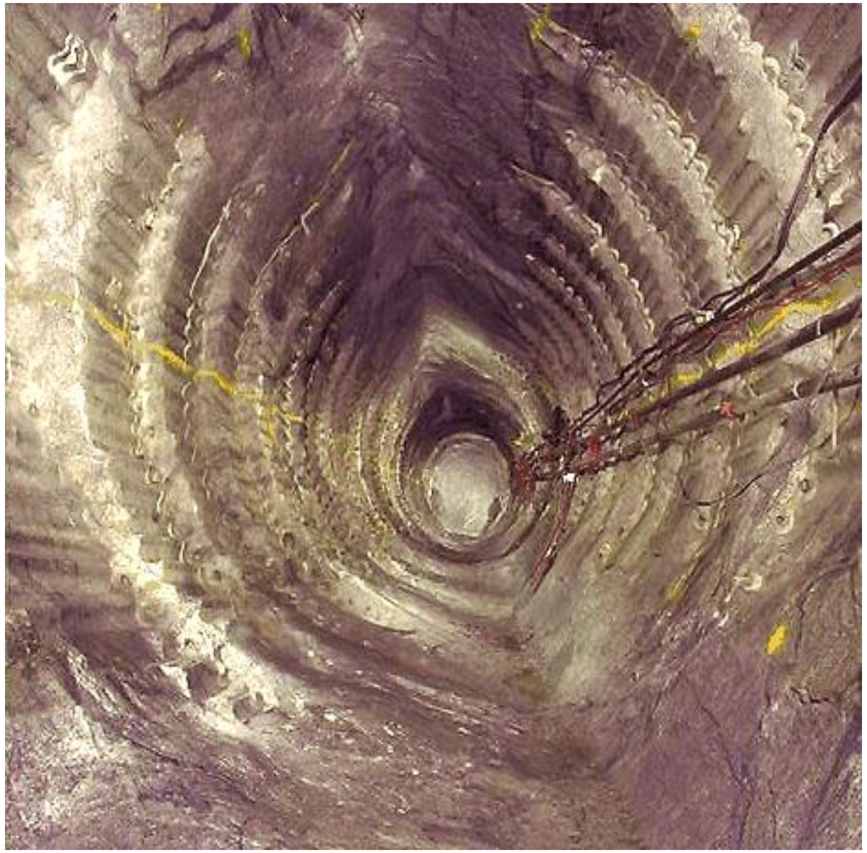
$$\sigma_1 = \sigma_3 + \sqrt{m\sigma_c\sigma_3 + s\sigma^2_c}$$



Stress induced damages

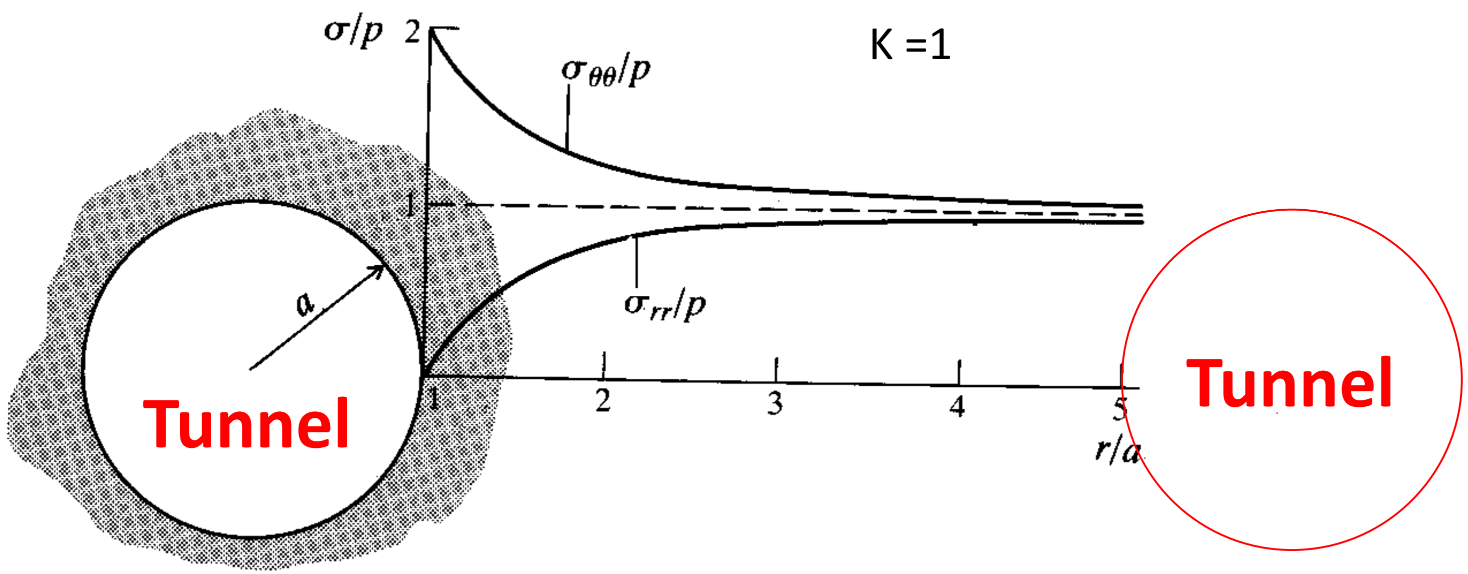
In good conditions





With breakout zone

Zone of influence of an excavation



$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right)-(1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right)+(1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{r\theta} = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

Zone of influence of an excavation

- Stresses die off rapidly as we move away from the opening boundary
- If a second excavation were generated outside the region defined by $r = 5a$ for the first excavation, the pre-mining stress field would not be significantly different from the virgin stress field
- Hence, holes more than **three diameters** apart (centre to centre distance) may be regarded as separate individual excavations, which do not interact with each other

Example

Use the Kirsch Equations to predict stresses around a circular tunnel with 4 m radius. Assume the rock mass is elastic with the following parameters: E = 10 GPa, μ = 0.25, specific gravity = 2.3. The insitu stress can be estimated assuming a depth of 500 m below the ground surface and k = 2.5 (k = horizontal/vertical insitu stress).

(a) Determine the vertical and the horizontal stresses of two points along a vertical line passing through the centre of the tunnel. The distances of two points are 4 m (point A) and 8 m (point B), respectively.

(b) Assume the tunnel above was created by a tunnel-boring machine. The rock type is sandstone with a GSI value estimated to be 55. The intact rock has a ucs of 60 MPa and a m_i value of 19. Determine the rock mass strength for the points A and B by using Hoek-Brown criterion.

(c) Would the rock mass failure occur in these two points?

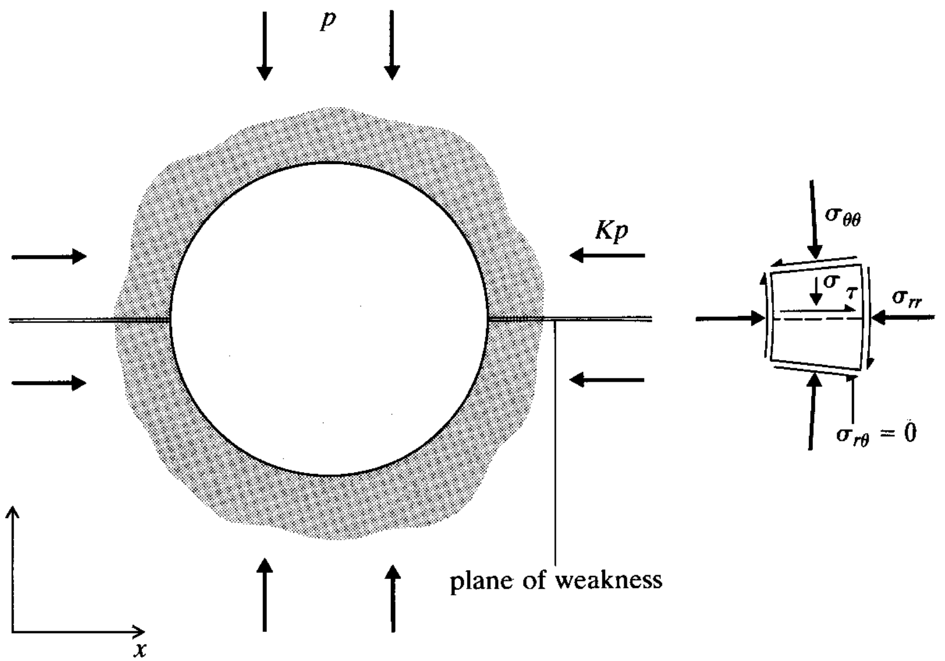
Effect of planes of weakness on elastic stress distribution - 1

- Assumption: discontinuity has zero tensile strength, and is non-dilatant in shear, with shear strength defined by

$$\tau = \sigma_n \tan\phi$$

- Discontinuity has no effect
  - there is no shear stress along the discontinuity

CASE 1



$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right) - (1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

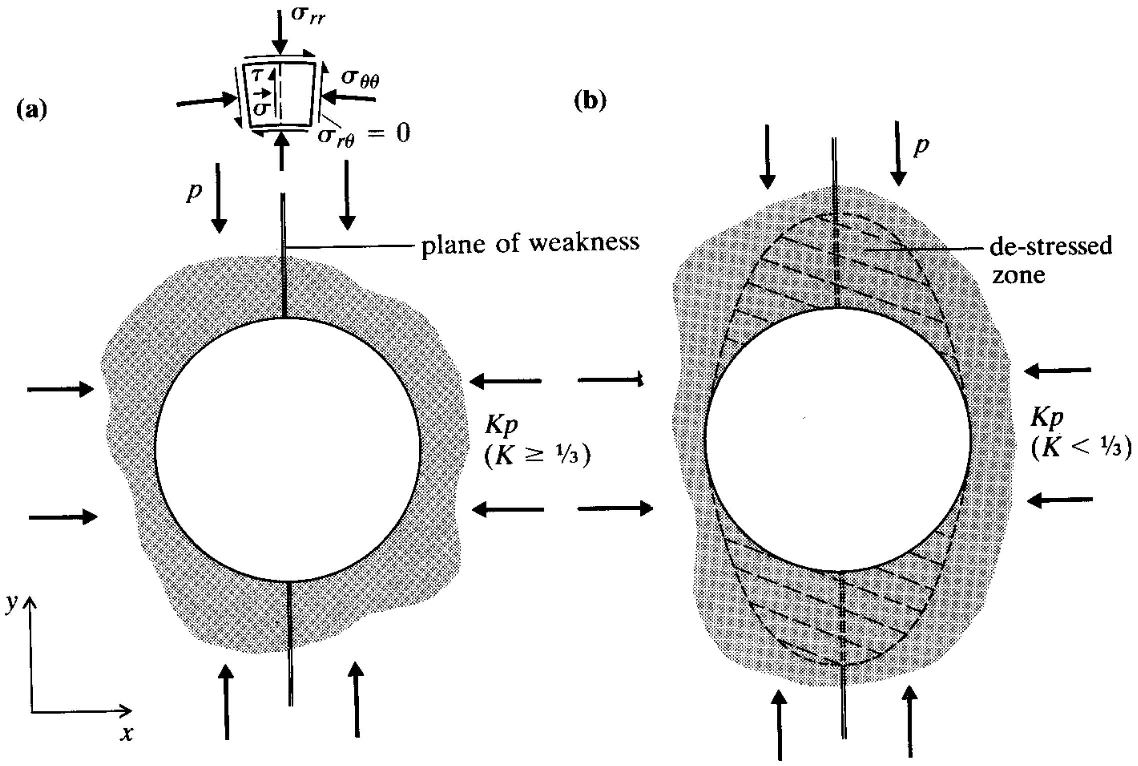
$$\sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right) + (1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{r\theta} = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

Effect of planes of weakness on elastic stress distribution - 2

- Presence of discontinuity can lead to de-stressed zone if tension is created in the roof/back

CASE 2



$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right)-(1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

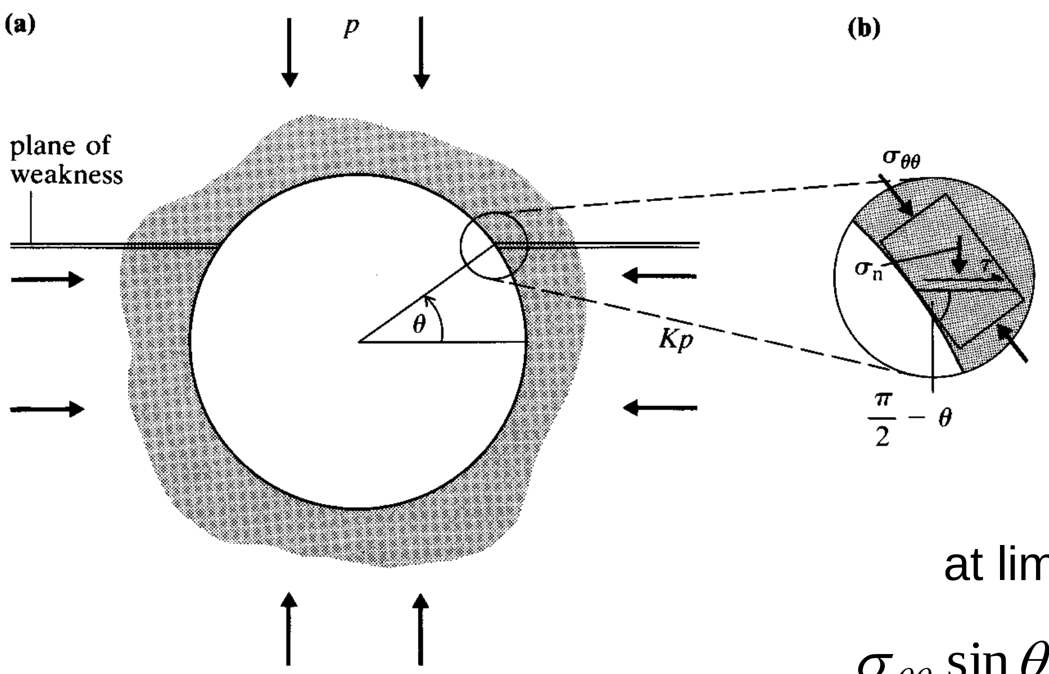
$$\sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right)+(1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{r\theta} = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

Effect of planes of weakness on elastic stress distribution - 3

- If $\vartheta=\phi$, then slip initiates
- Sense of shear results in outward movement of hanging wall; this tends to reduce clamping stresses near roof

CASE 3



$$\sigma_{rr}=\frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right)-(1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{\theta\theta}=\frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right)+(1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{r\theta}=\frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

$$\sigma_n=\sigma_{\theta\theta}\cos^2\theta \qquad \tau=\sigma_{\theta\theta}\sin\theta\cos\theta$$

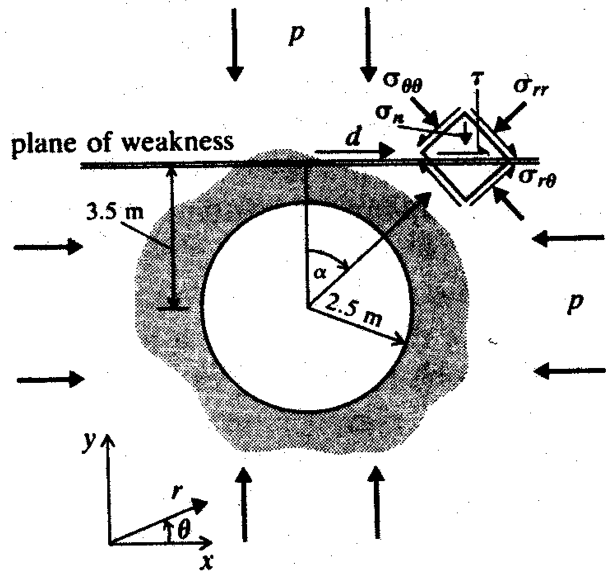
at limit equilibrium

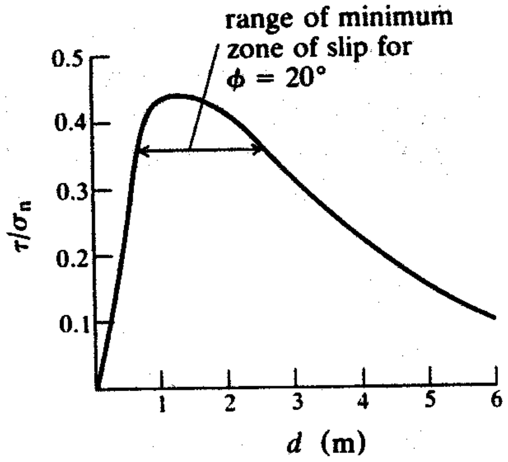
$$\sigma_{\theta\theta}\sin\theta\cos\theta=\sigma_{\theta\theta}\cos^2\theta\tan\phi \qquad \tan\theta=\tan\phi$$

Effect of planes of weakness on elastic stress distribution - 5

- Assume lithostatic stress
- Shear stress/normal stress ratio relates to a mobilized angle of friction
- If $\phi > 24º$ then no slip and elastic conditions prevail

CASE 5





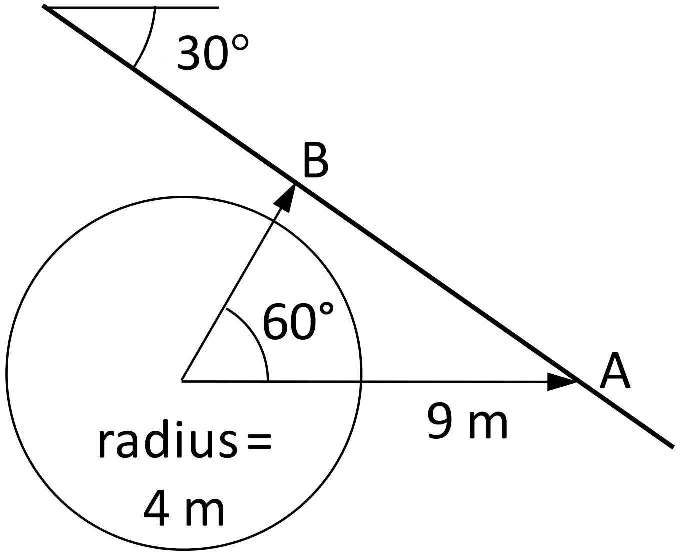
$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right) - (1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right) + (1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{r\theta} = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

Example

In-situ horizontal stress = 10 MPa, in-situ vertical stress = 5 MPa. Calculate the normal and shear stress acting at points A and B on an inclined planar fault located near the tunnel. The fault dips 30° and strikes parallel to the tunnel axis. Indicate the sense of shear at both locations via a simple sketch.



$$\sigma_{rr} = \frac{p}{2}\left[(1+K)\left(1-\frac{a^2}{r^2}\right)-(1-K)\left(1-4\frac{a^2}{r^2}+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{\theta\theta} = \frac{p}{2}\left[(1+K)\left(1+\frac{a^2}{r^2}\right)+(1-K)\left(1+\frac{3a^4}{r^4}\right)\cos 2\theta\right]$$

$$\sigma_{r\theta} = \frac{p}{2}\left[(1-K)\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)\sin 2\theta\right]$$

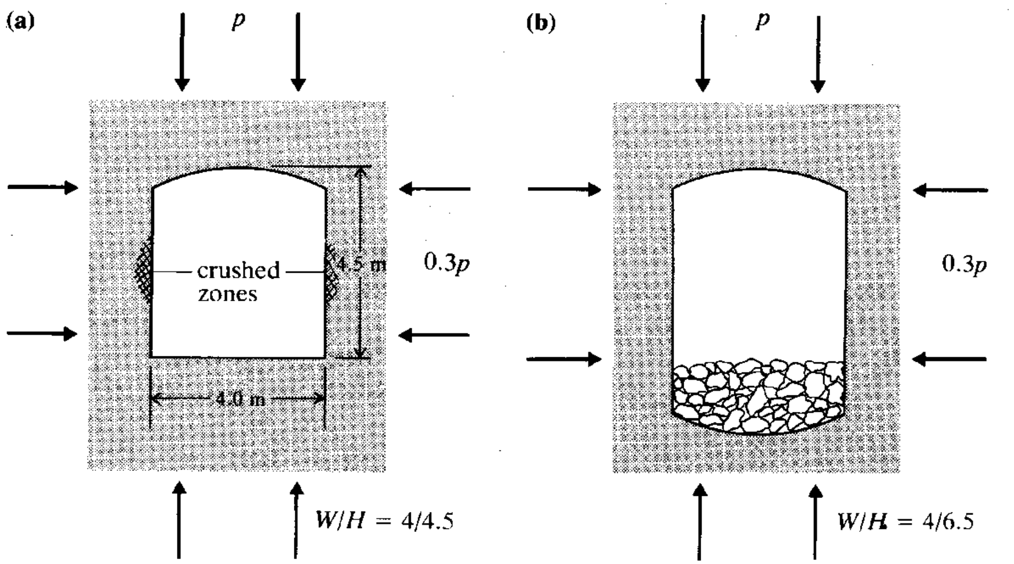
$$\sigma'_x = \sigma_x \cos^2\theta + \sigma_y \sin^2\theta + 2\tau_{xy}\sin\theta\cos\theta$$

$$\sigma'_y = \sigma_x \sin^2\theta + \sigma_y \cos^2\theta - 2\tau_{xy}\sin\theta\cos\theta$$

$$\tau'_{xy} = (\sigma_y - \sigma_x)\cos\theta\sin\theta + \tau_{xy}(\cos^2\theta - \sin^2\theta)$$

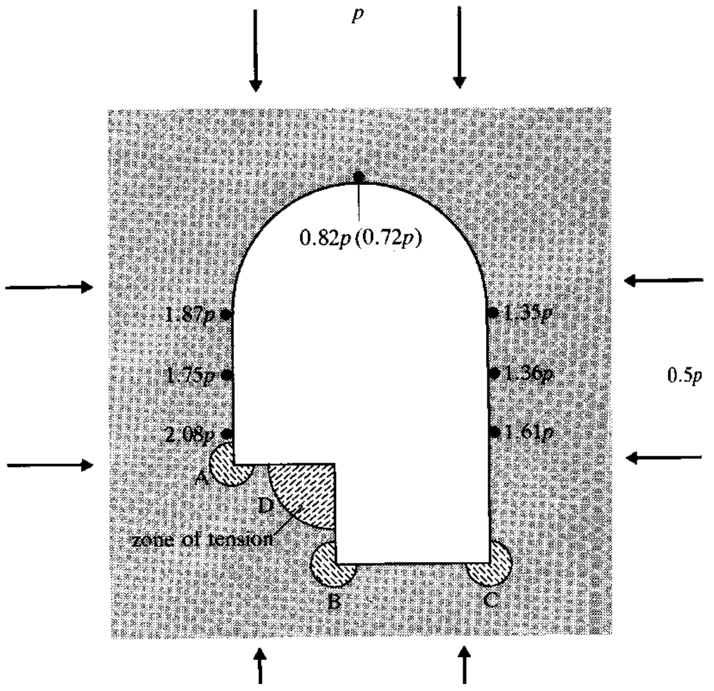
Excavation shape

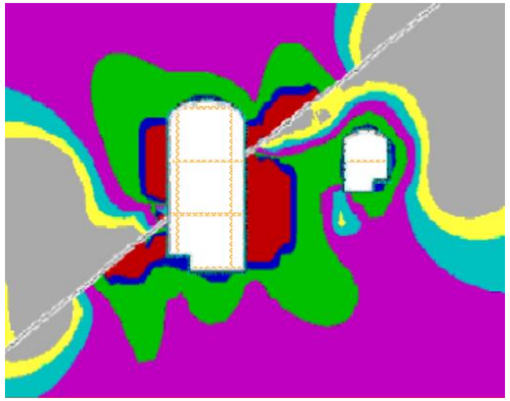
- Can use elliptical openings to minimize stress concentrations in a non-lithostatic stress field
- Opening dimension is increased in the direction of the major principal stress
- If axis ratio for the elliptical opening matches the stress ratio then the boundary stresses will be uniform



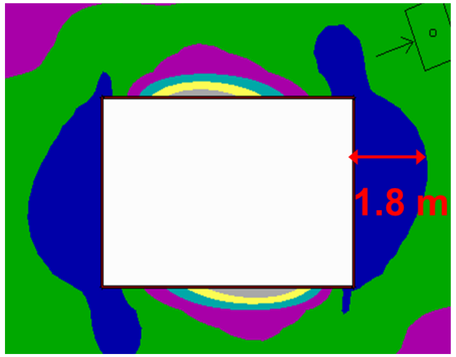
Excavation shape

- Zones, A, B, C are likely highly stressed, since the boundary curvature is high
- Bench area D is at a low state of stress
- Boundary stress at the crown would be about 0.82*p*
- Sidewall stresses are shown
- Stress can be estimated using computation simulations





Predicted



Observed