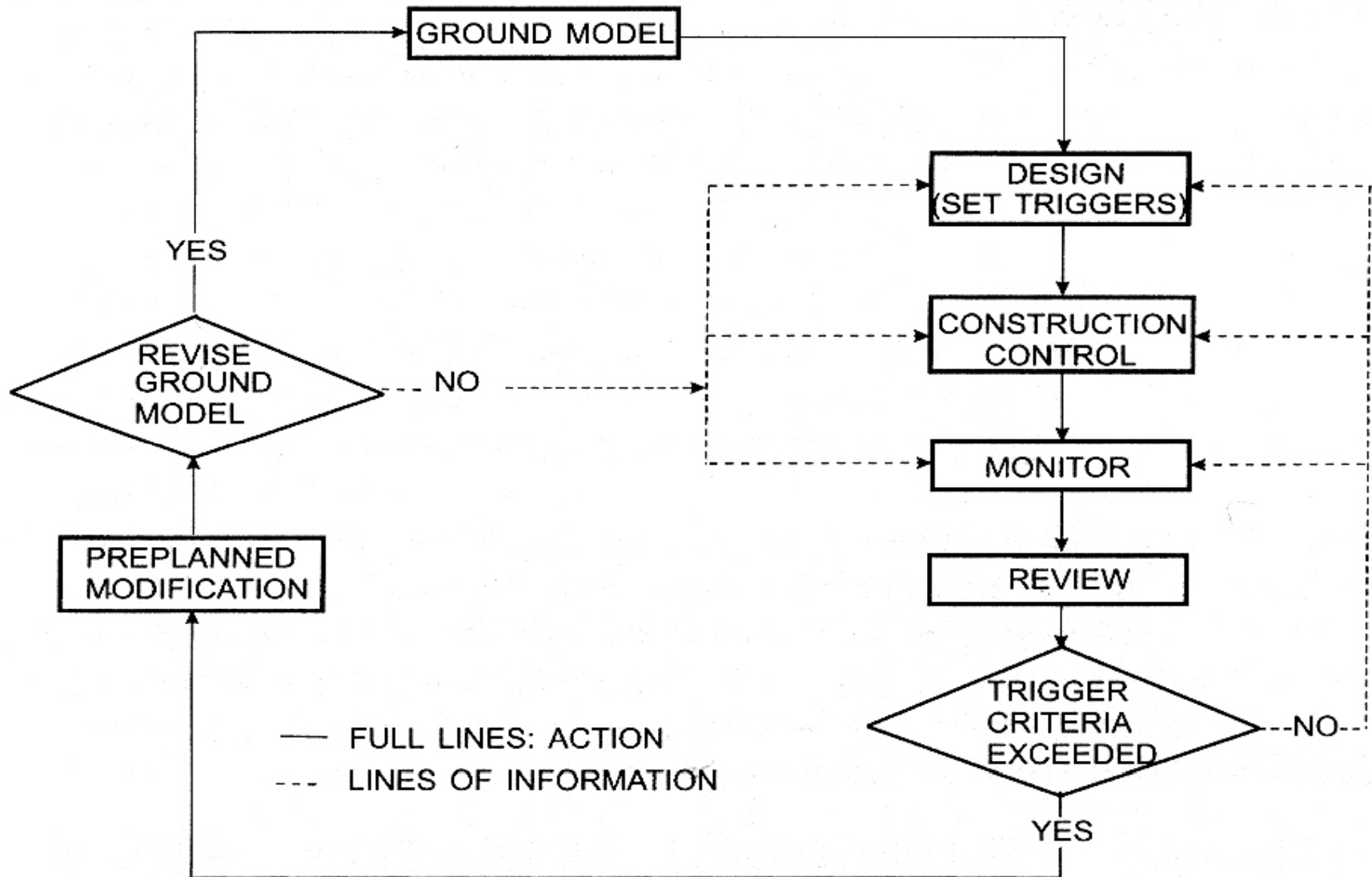


# **Observational Methods and NATM**

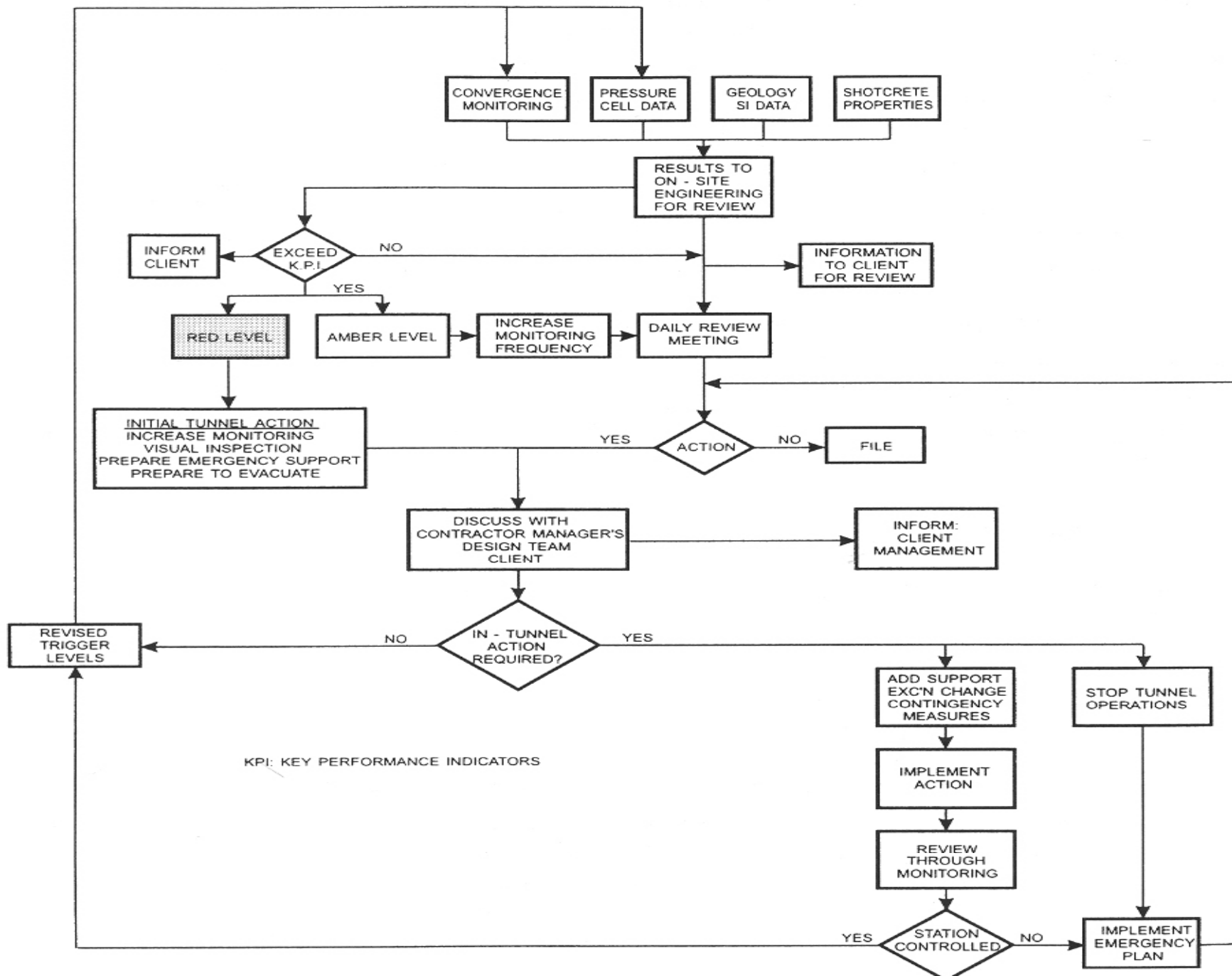
# System for Observational approach to tunnel design



Eurocode 7 (EC7) includes the following remarks concerning an observational method.

Four requirements shall all be made before construction is started:

- ***The limits of behaviour***, which are acceptable, shall be established.
- ***The range of behaviour*** shall be assessed and it shall be shown that there is an acceptable probability that the ***actual behaviour will be within the acceptable limits***.
- ***A plan of monitoring*** shall be devised which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a ***sufficient early stage; and with sufficiently short intervals to allow contingency actions to be undertaken successfully***. The response time on the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system.
- ***A plan of contingency actions shall be devised*** which may be adopted if the monitoring reveals behaviour outside acceptable limits.  
***During construction the monitoring shall be carried out as planned and additional or replacement monitoring shall be undertaken if this becomes necessary. The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put in operation if this becomes necessary.***



# NATM – New Austrian Tunnelling Method

One of the most well known methods using some elements of an observational approach is the New Austrian Tunnelling Method, or NATM. The method, has often been mentioned as a ‘value engineered’ version of tunnelling due to its use of light, informal support. It has long been understood that the ground, if allowed to deform slightly, is capable of contributing to its own support. NATM, with its use of modern means of monitoring and surface stabilisation, such as shotcrete and rock bolts, utilizes this effect systematically.

- ***Traditional tunnelling*** used first timber supports and later on steel arch supports in order to stabilise a tunnel temporarily until the final support was installed. The final support was masonry or a concrete arch. Rock loads developed due to disintegration and detrimental loosening of the surrounding rock and loosened rock exerted loads onto the support due to the weight of a loosened rock bulb (described by Komerell, Terzaghi and others). Detrimental loosening was caused by the available excavation techniques, the support means and the long period required to complete a tunnel section with many sequential intermediate construction stages. The result was very irregular heavy loading resulting in thick lining arches occupying a considerable percentage of the tunnel cross-section (in the early trans-Alpine tunnels the permanent structure may occupy as much as 40% of the excavated profile)

**NATM: With a flexible primary support a new equilibrium shall be reached. This shall be controlled by in-situ deformation measurements. After this new equilibrium is reached an inner arch shall be built. In specific cases the inner arch can be omitted.**

- The New Austrian Tunnelling Method constitutes a design where the surrounding rock- or soil formations of a tunnel are integrated into an overall ring like support structure. Thus the formations will themselves be part of this support structure.
- With the excavation of a tunnel the primary stress field in the rock mass is changed into a more unfavourable secondary stress field. Under the *rock arch* we understand those zones around a tunnel where most of the time dependent stress rearrangement processes takes place. This includes the plastic as well as the elastic behaving zone.
- Under the *activation of a rock arch* we understand our activities to maintain or to improve the carrying capacity of the rock mass, to utilise this carrying capacity and to influence a favourable development of the secondary stress field.

### ***The main principles of NATM are:***

- The main load-bearing component of the tunnel is the surrounding rock mass. Support is 'informal' i.e. it consists of earth/rock-anchors and shotcrete, but support and final lining have confining function only.
- **Maintain strength of the rock mass** and avoid detrimental loosening by careful excavation and by immediate application of support and strengthening means. Shotcrete and rock bolts applied close to the excavation face help to maintain the integrity of the rock mass.
- **Rounded tunnel shape**: avoid stress concentrations in corners where progressive failure mechanisms start.
- **Flexible thin lining**: The primary support shall be thin-walled in order to minimise bending moments and to facilitate the stress rearrangement process without exposing the lining to unfavourable sectional forces. Additional support requirement shall not be added by increasing lining thickness but by bolting. ***The lining shall be in full contact with the exposed rock. Shotcrete fulfils this requirement.***
- Statically the tunnel is considered as a thick-walled tube consisting of the rock and lining. The closing of the ring is therefore important, i.e. **the total periphery including the invert must be applied with shotcrete.**
- **In situ measurements**: Observation of tunnel behaviour during construction is an integral part of NATM. With the monitoring and interpretation of deformations, strains and stresses it is possible to optimise working procedures and support requirements.



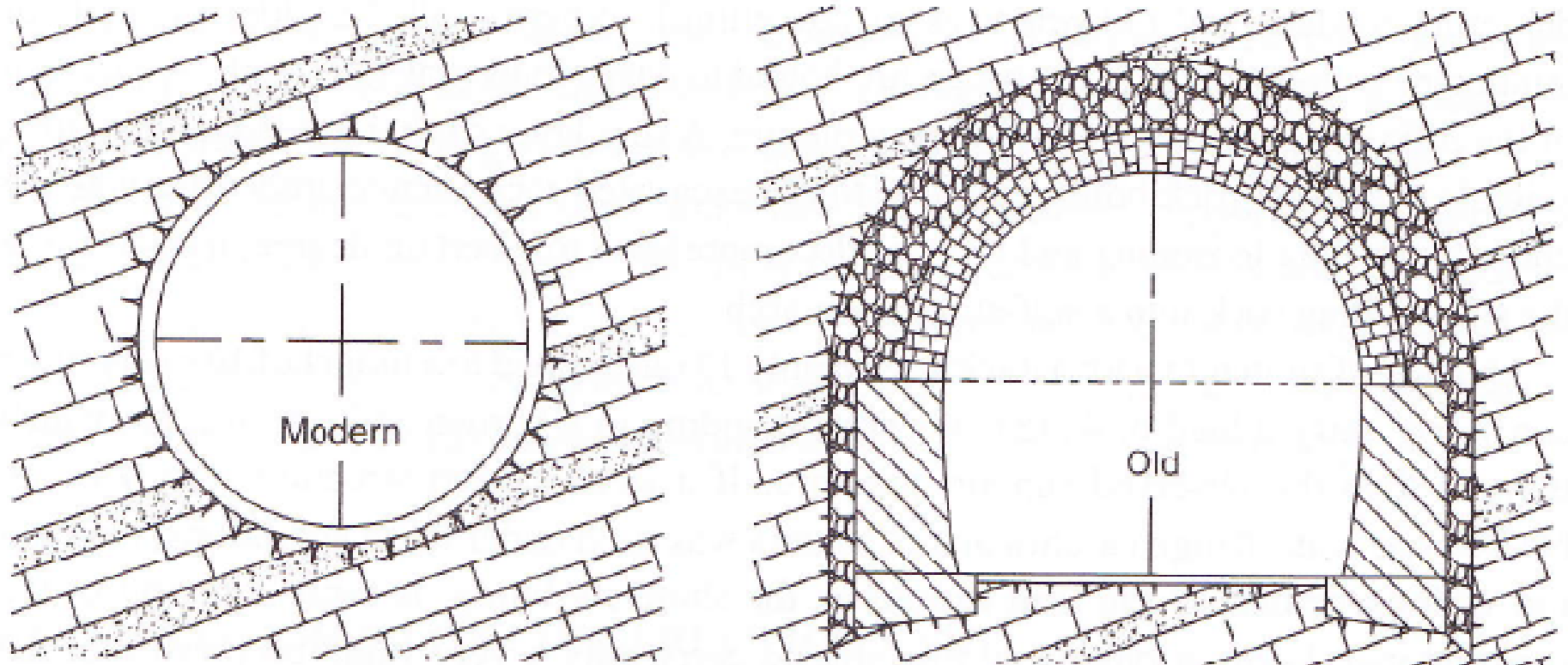


Fig. 9.1 The main load carrying member is the rock mass.

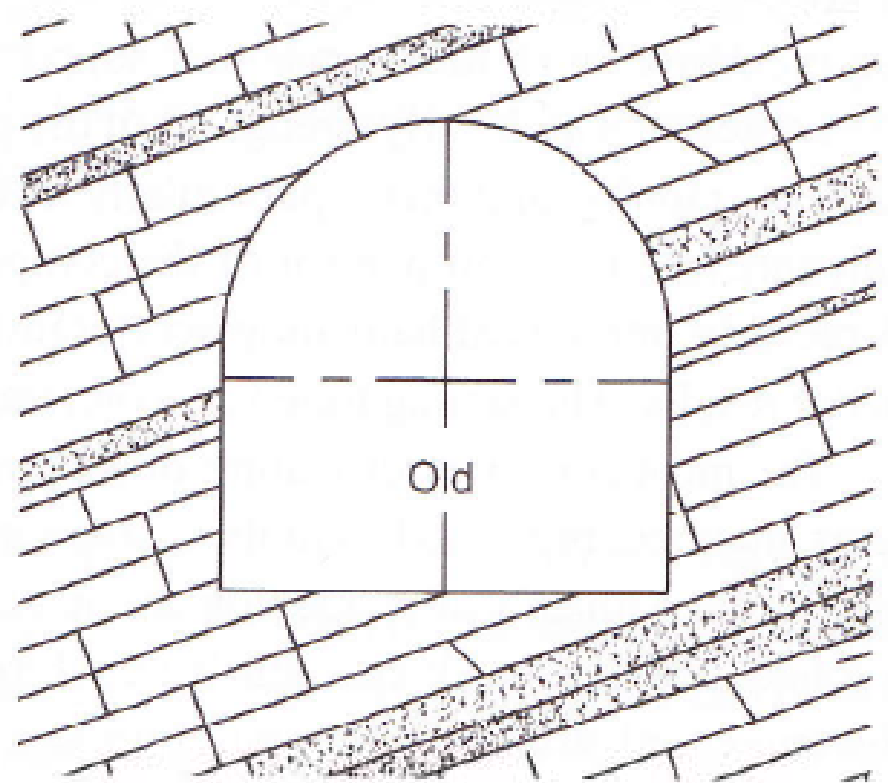
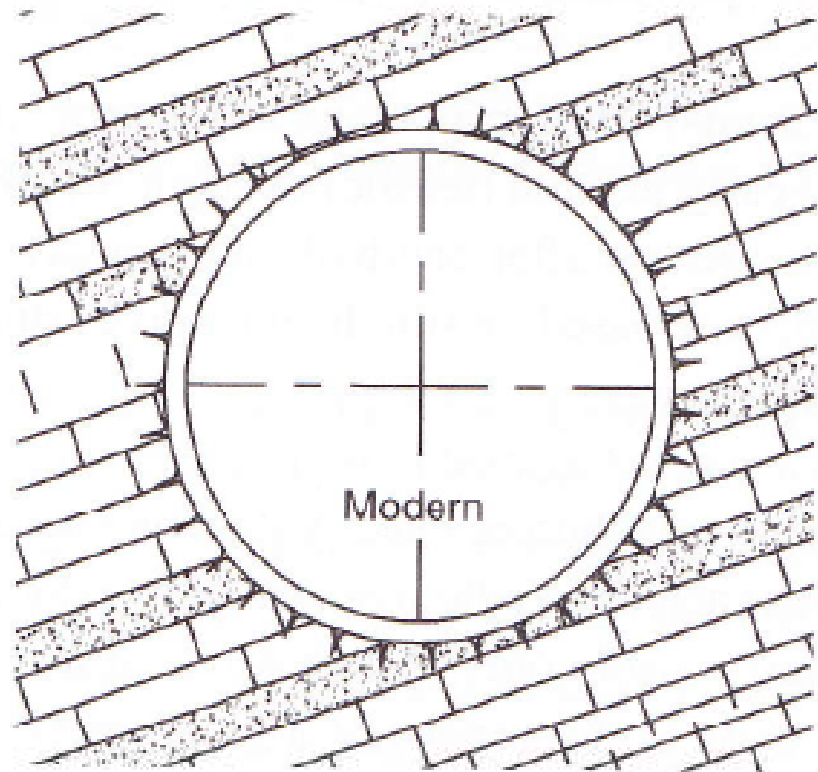


Fig. 9.2 Maintenance of original rock mass strength.

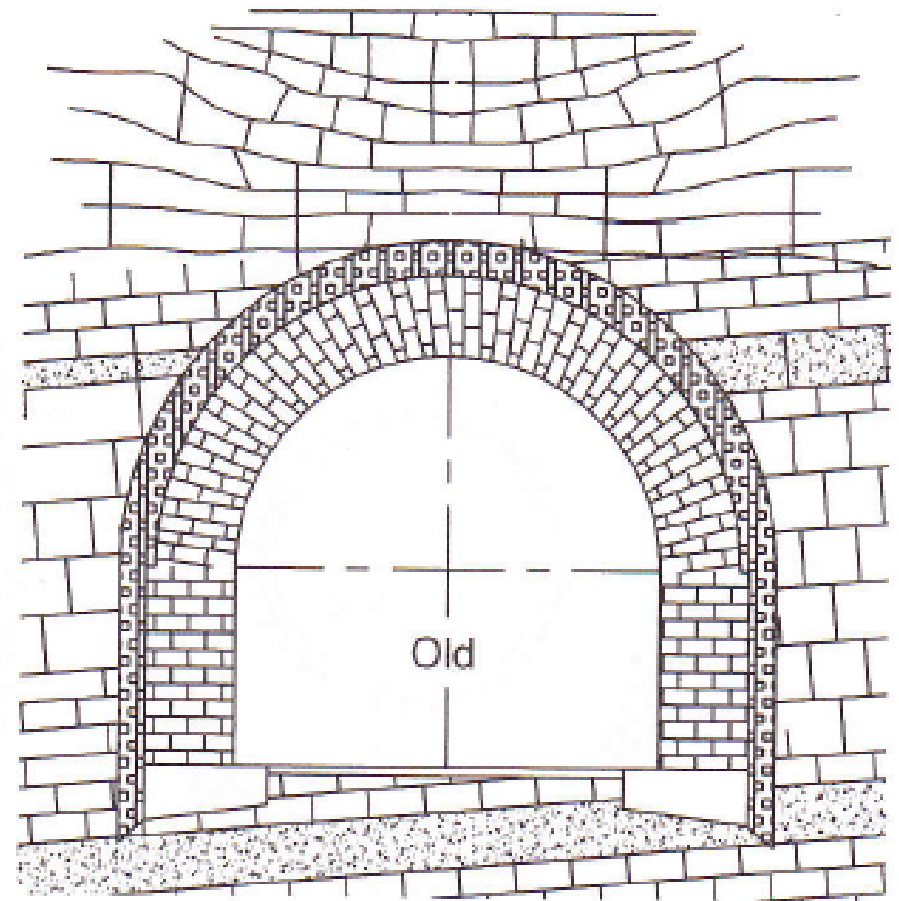
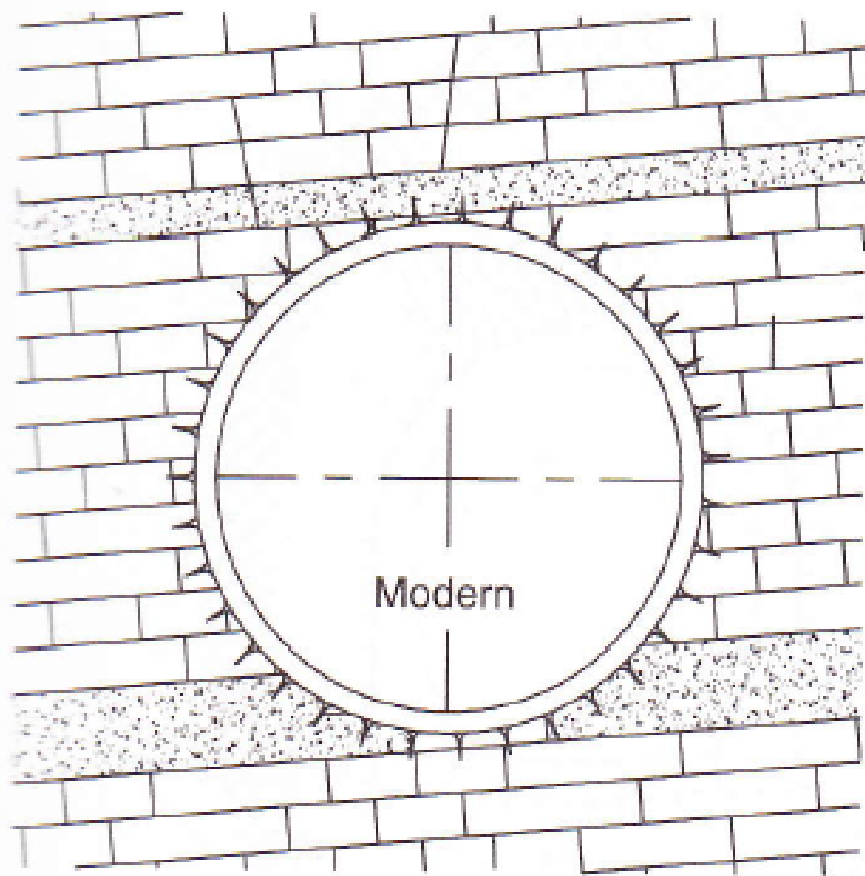


Fig. 9.3 Loosening must be prevented as it reduces strength.

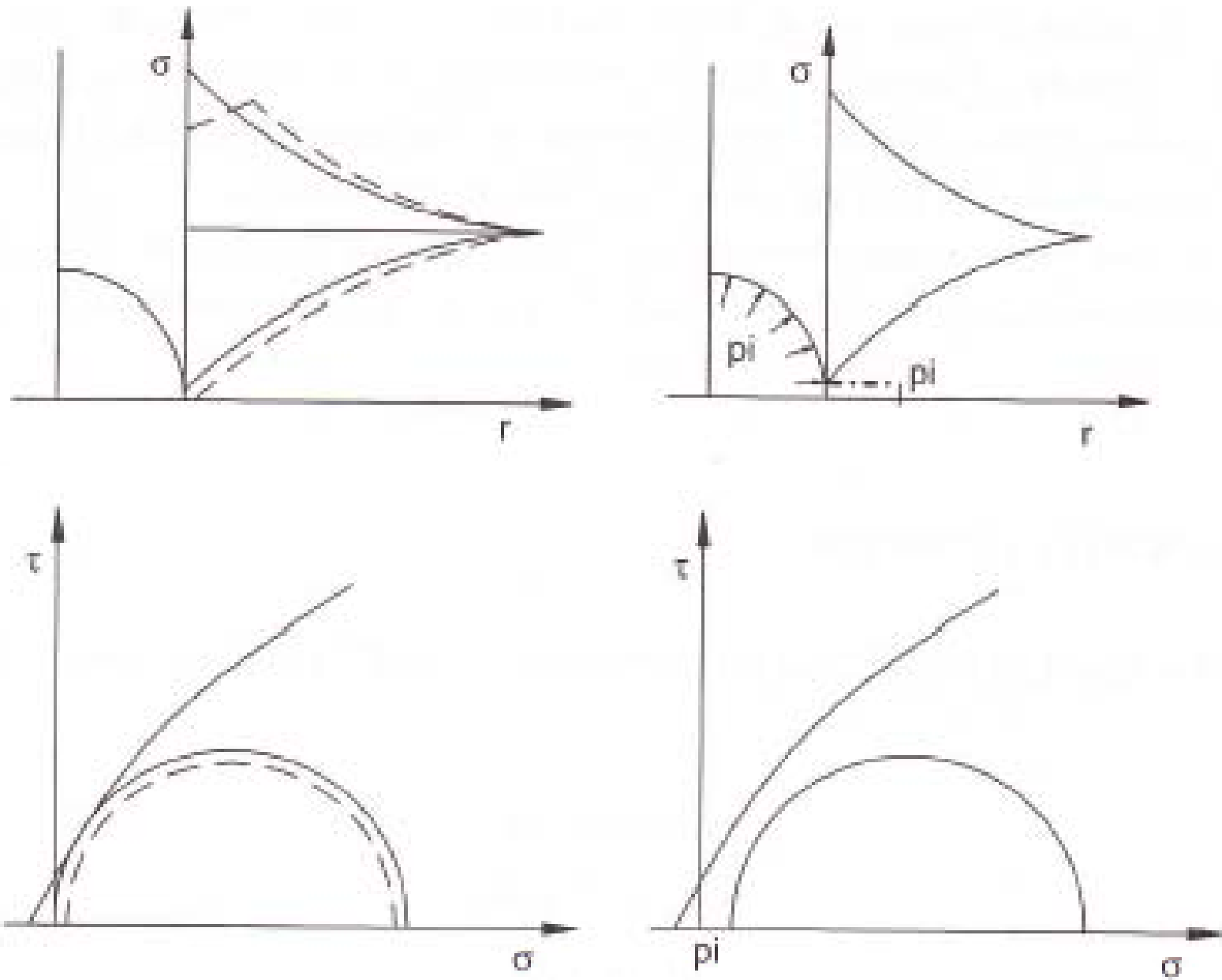


Fig. 9.4 Uniaxial stress condition should be prevented.

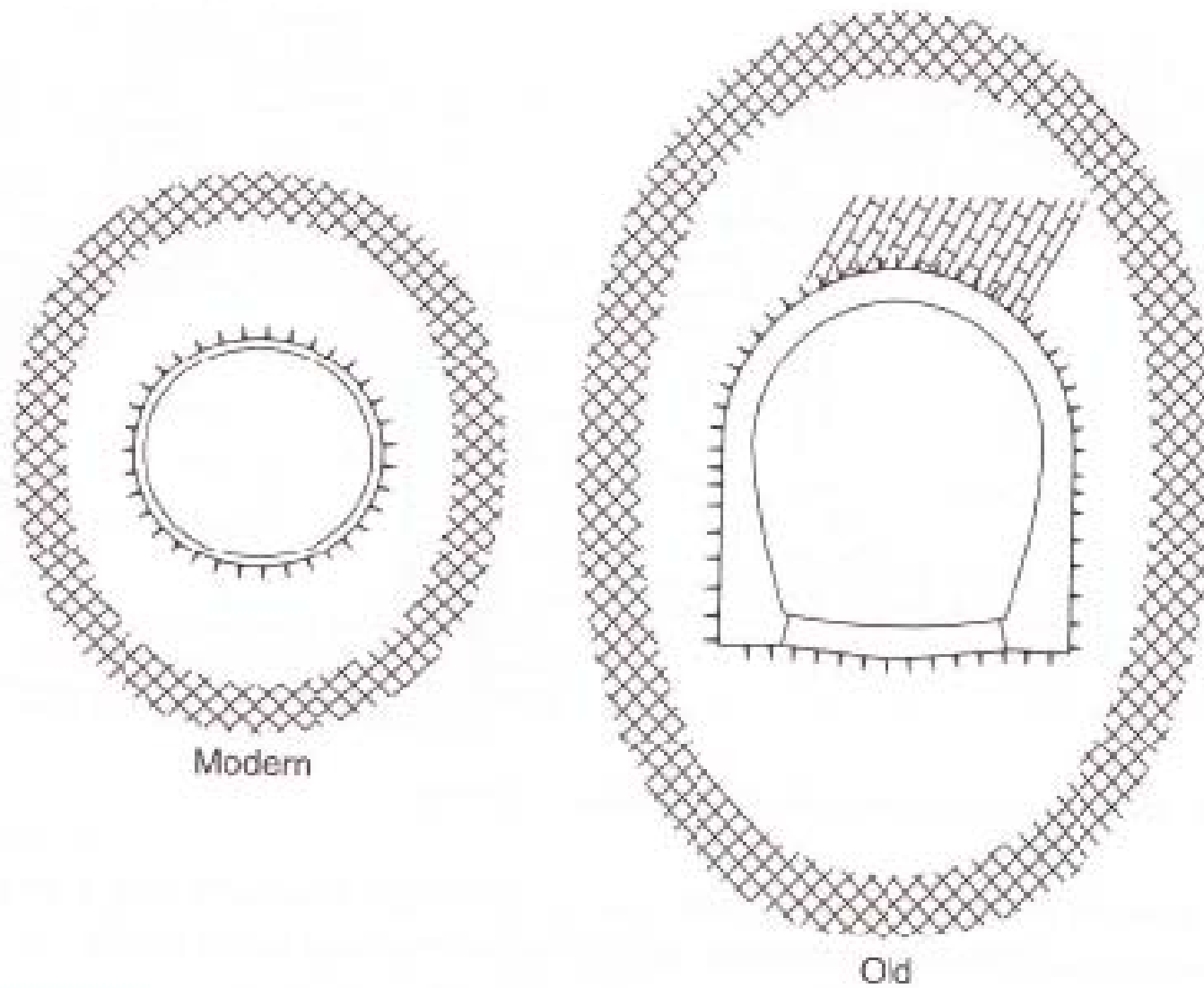


Fig. 9.5 Mobilization of the protective ring (rock carrying ring) without strength reduction.

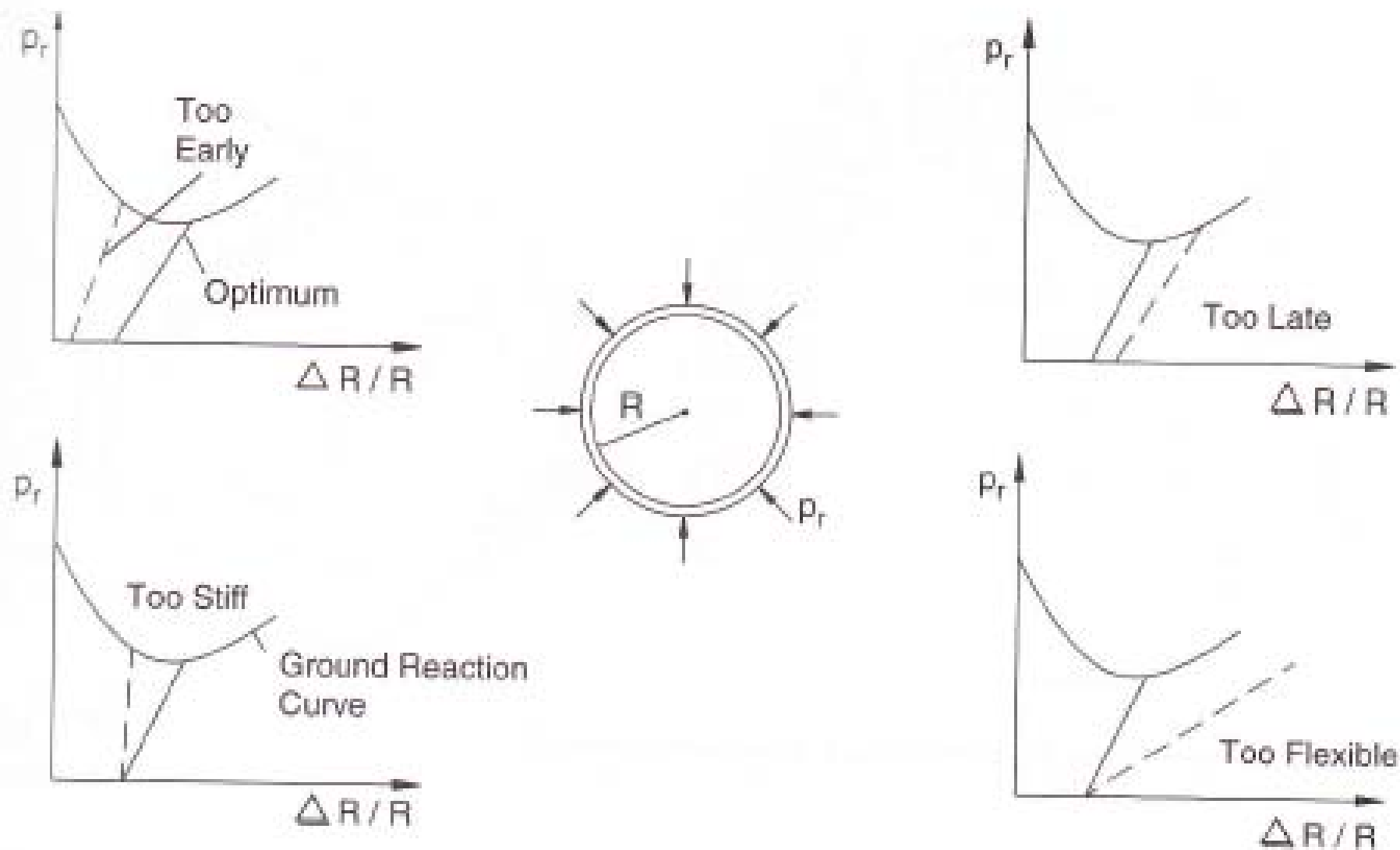


Fig. 9.6 Support (external lining) not too early, not too late, not too stiff, not too flexible.

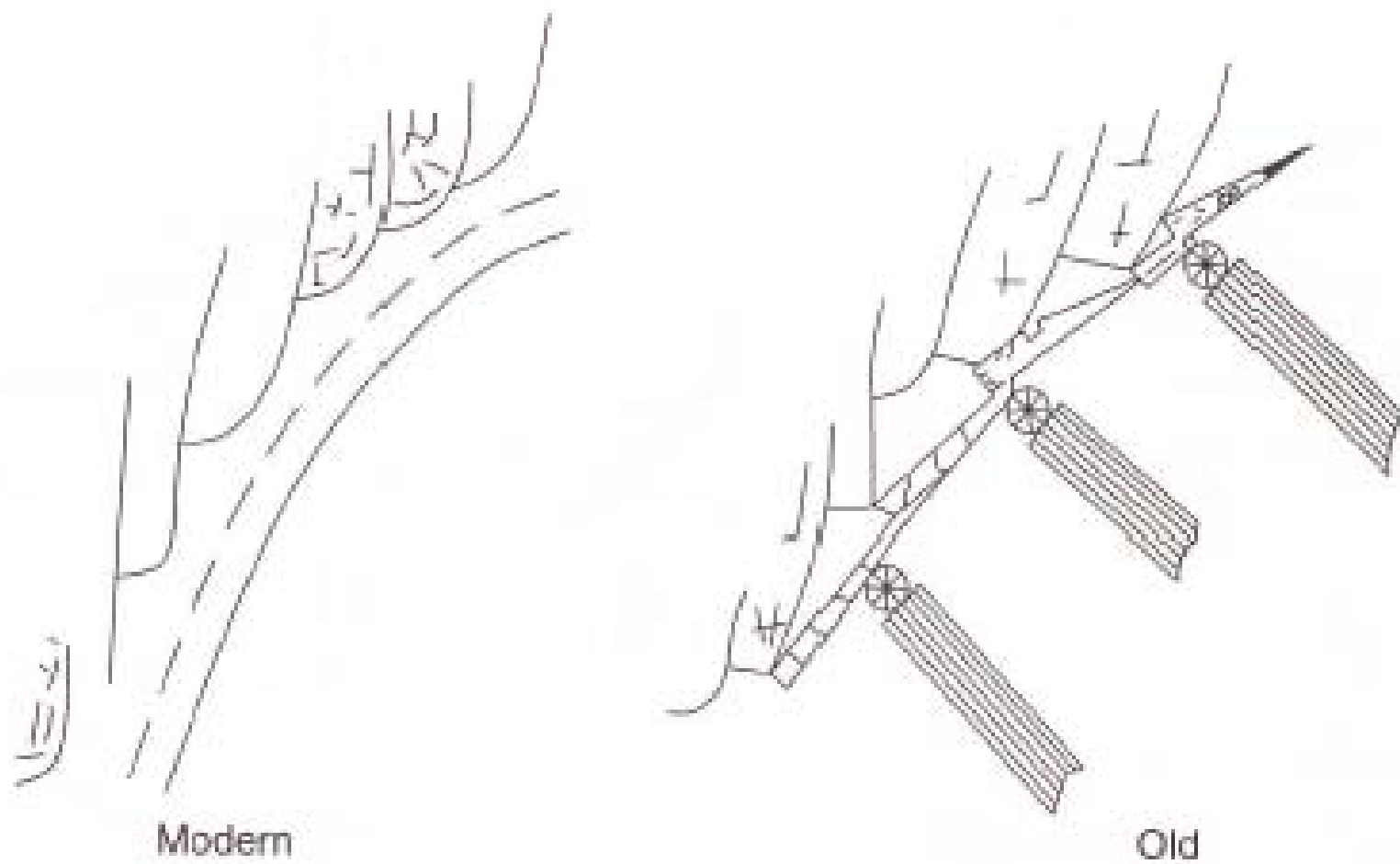


Fig. 9.7 Supports must be effective not at spots but overall.

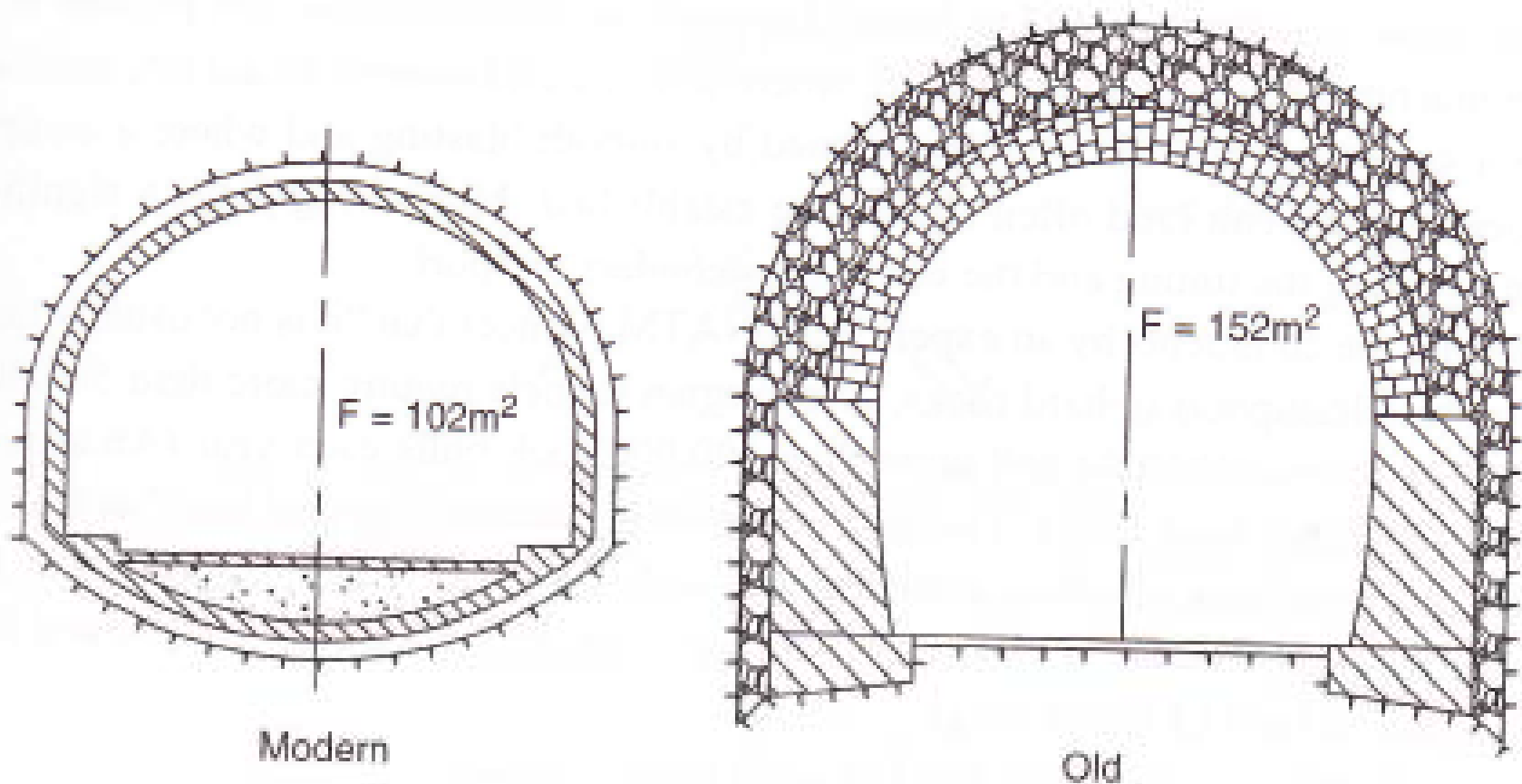


Fig. 9.8 Support should consist of thin linings which are flexible to bending. Ability to carry bending moments and bending failure is reduced.



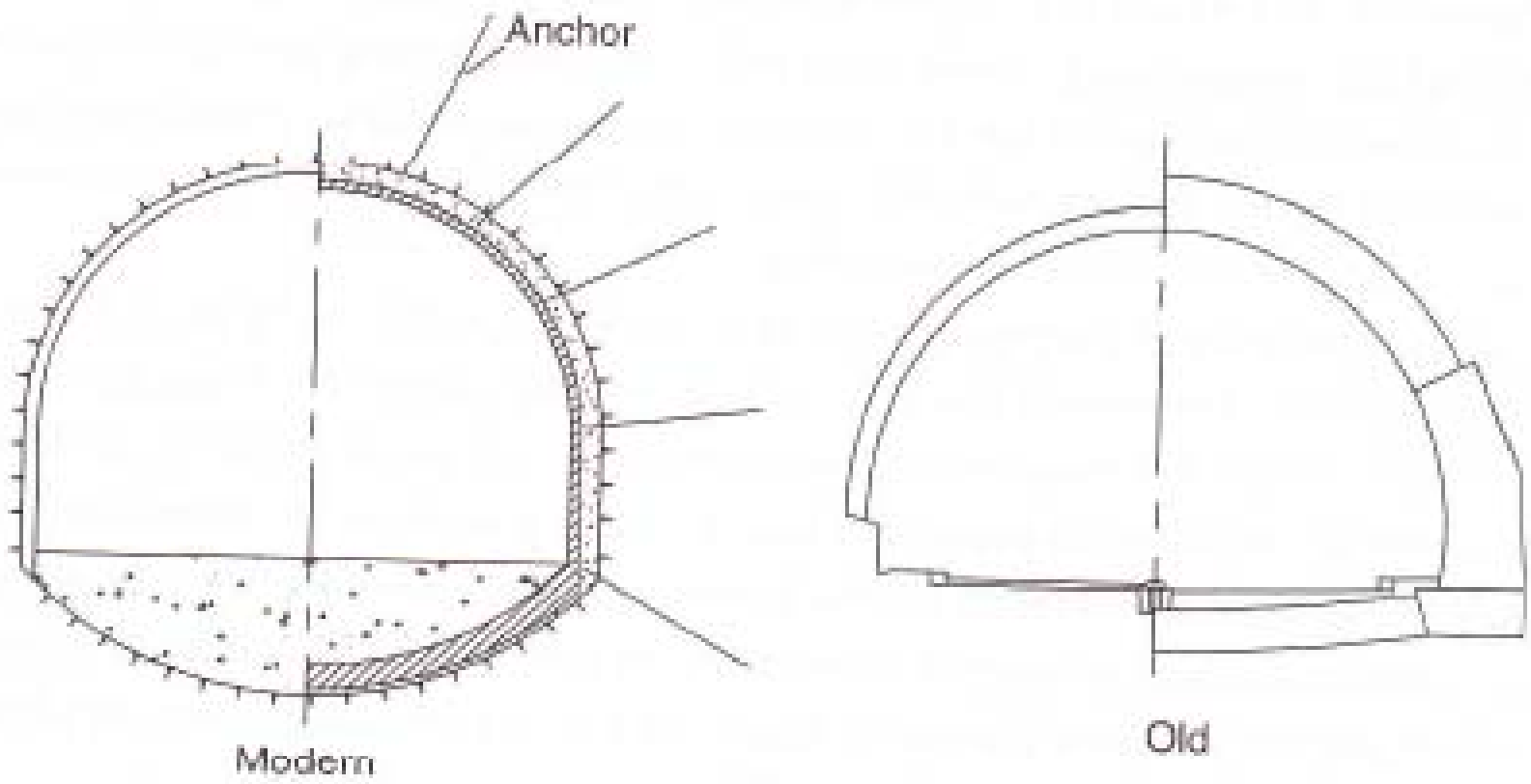


Fig. 9.9 Additional support should be provided by wire meshes, steel arches and anchorage. Not by increase of concrete thickness.

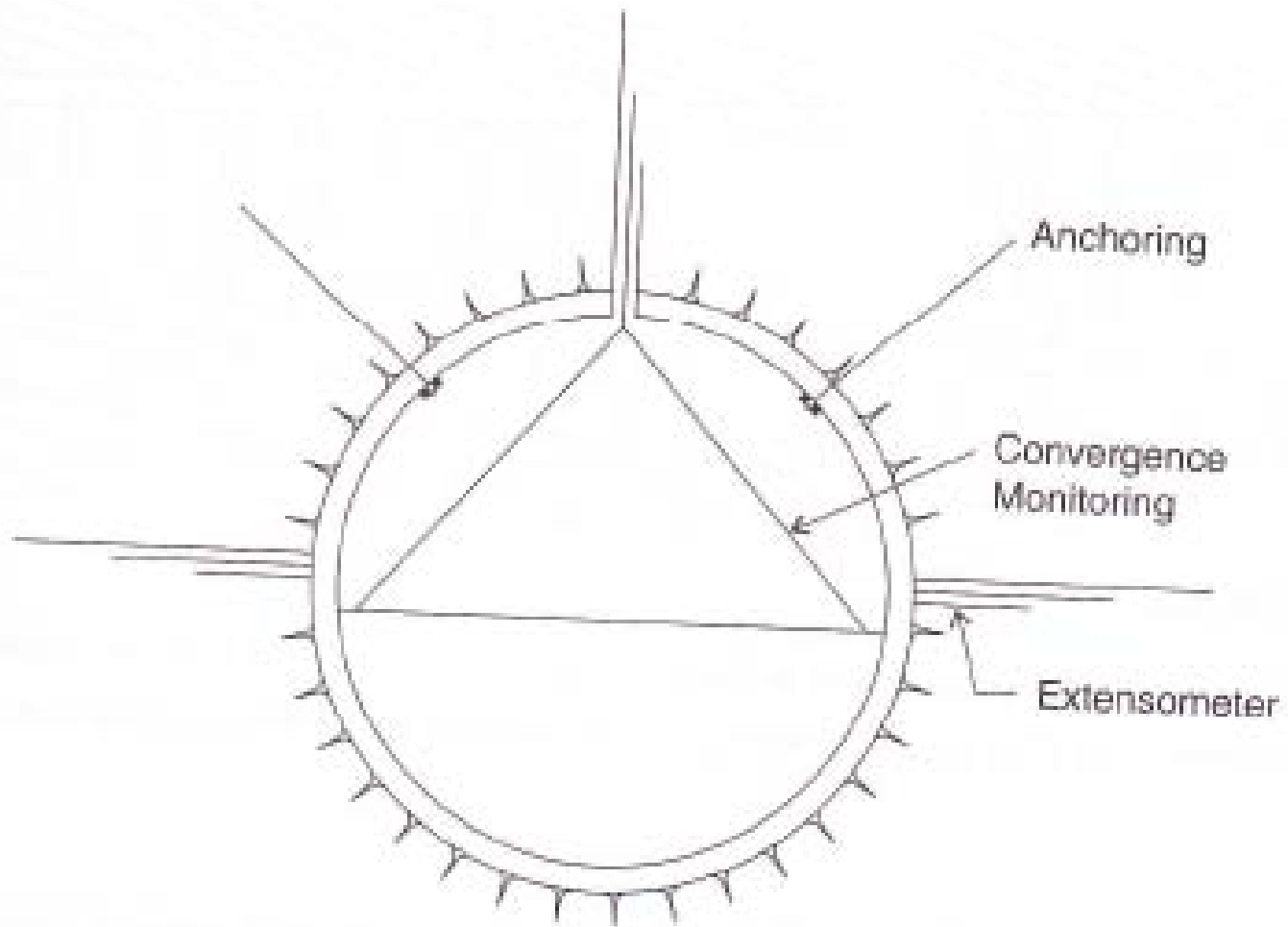


Fig. 9.10 Necessary support and its timing should be adjusted according to the measuring of the displacement.

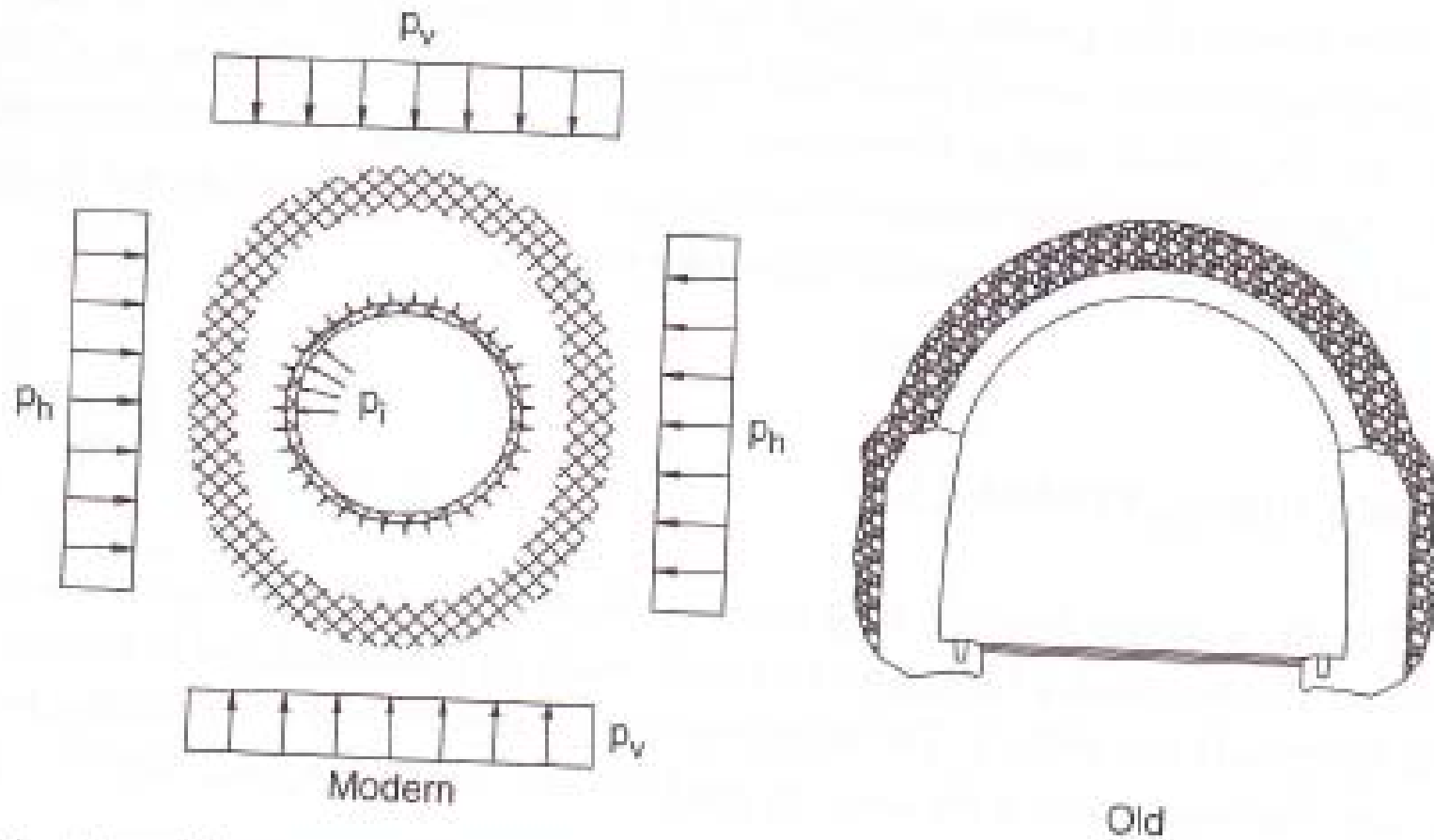
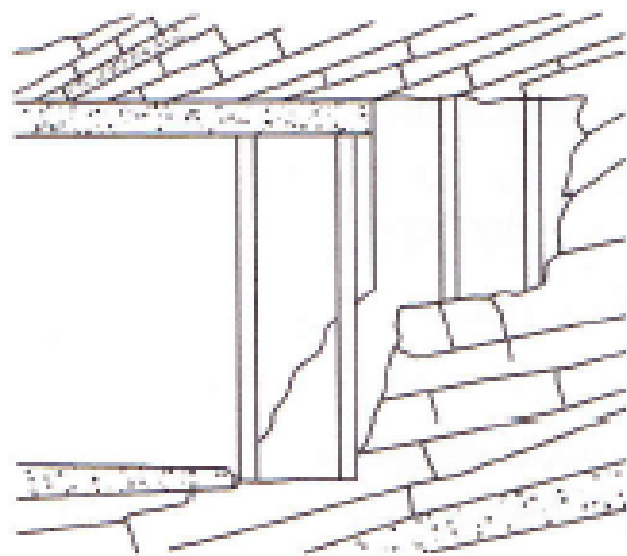
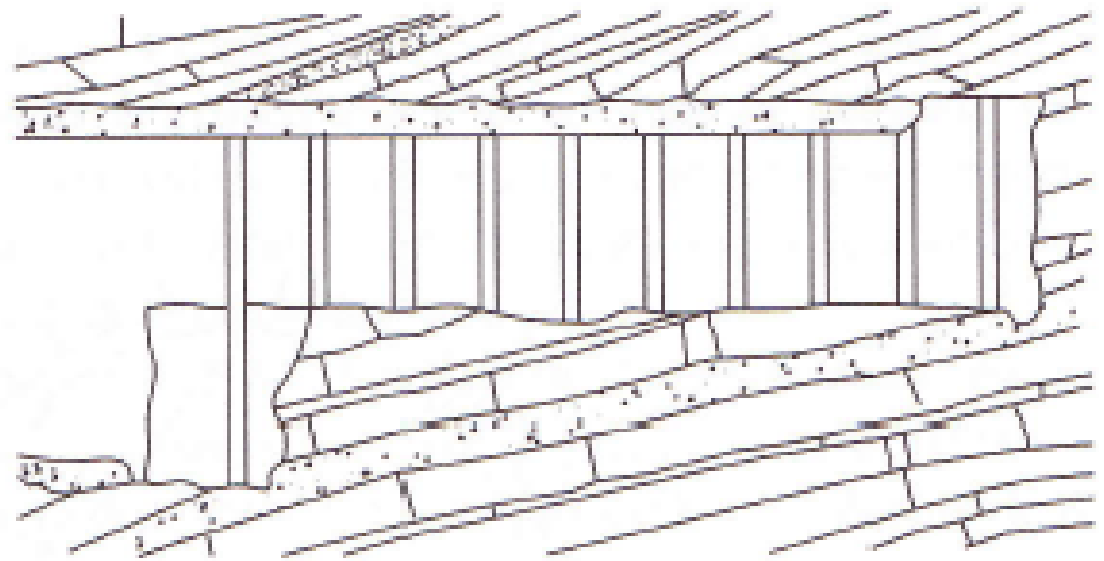


Fig. 9.11 According to rock mechanics, the tunnel is a tube which consists of the rock carrying ring and the support, not a conduit.



Modern



Old

Fig. 9.12 Behavior of the rock will be influenced by the delay of ring closure, advanced crown, increase delay, bending effect on the crown and increasing loads on the rock foundation.

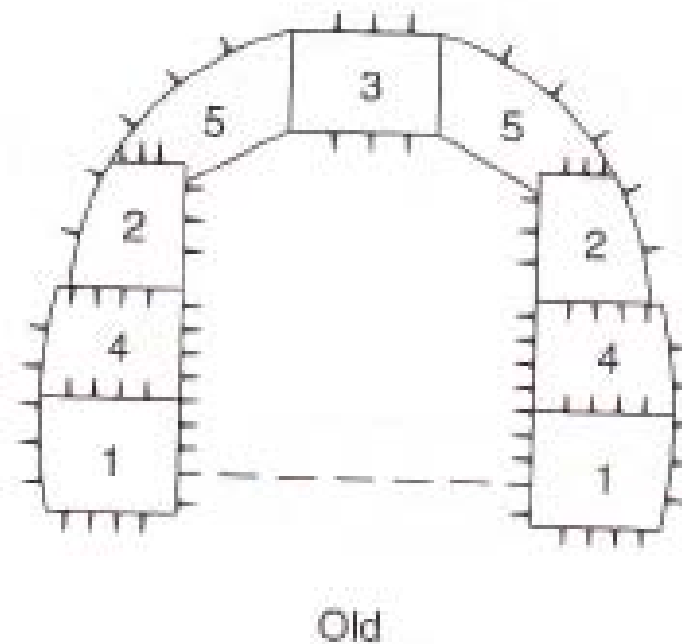
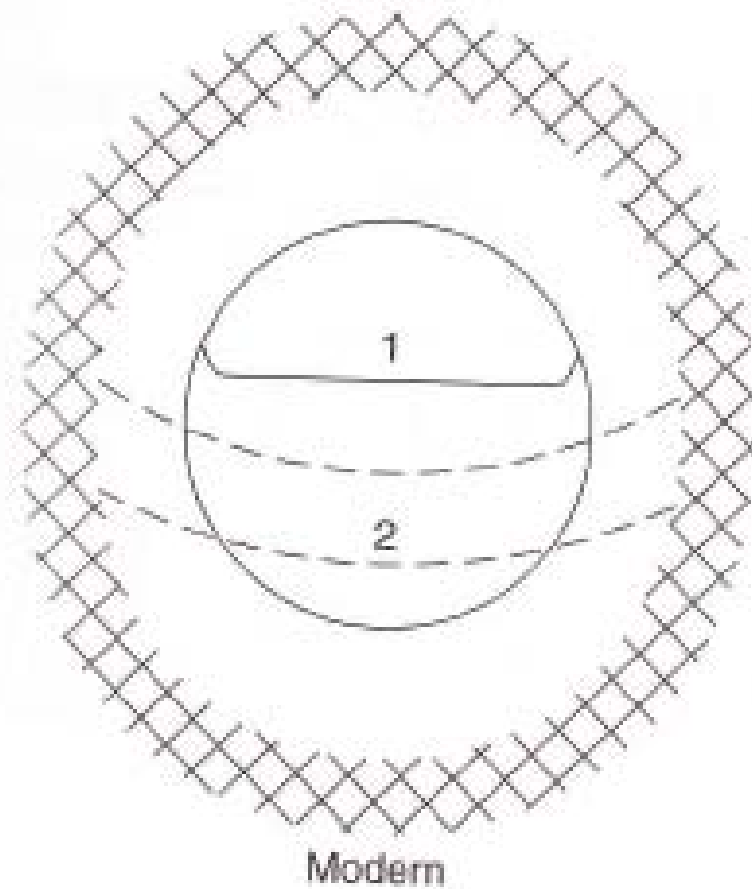
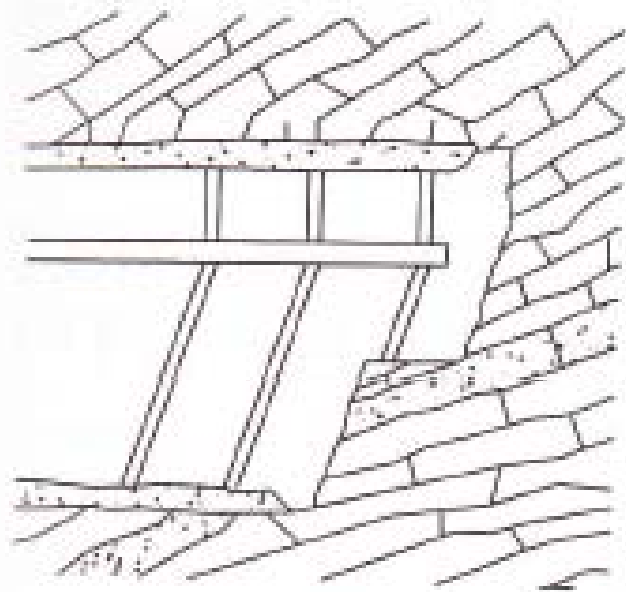
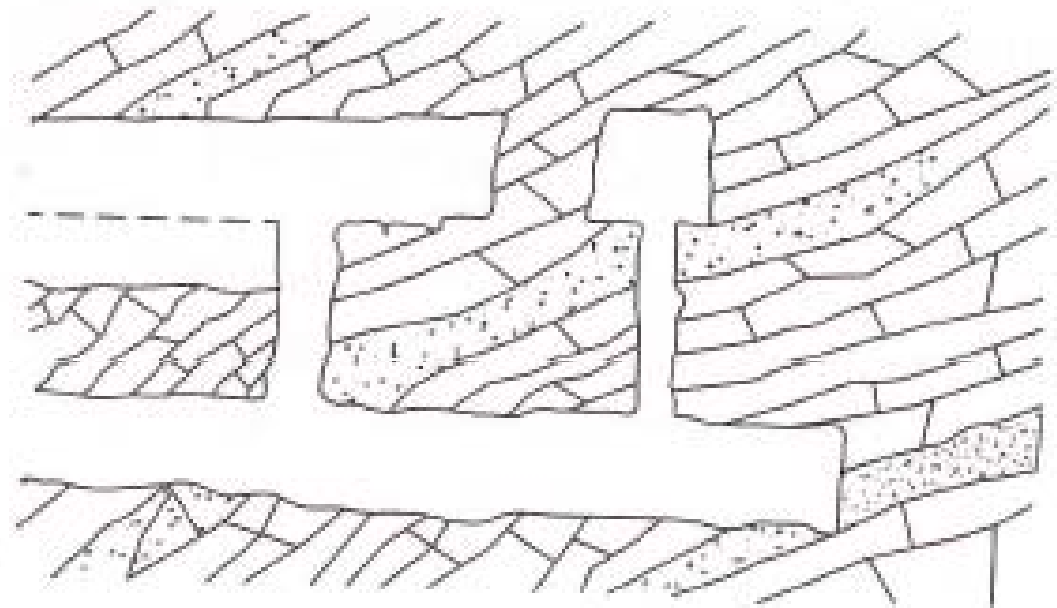


Fig. 9.13 Full-face heading helps to keep rock mass strength. Many partial headings reduce rock strength according to stress superposition.



Modern



Old

Fig. 9.14 Procedure of construction is important for safety of the structure. Variation of duration of a round, timing of support and ring closure, length of the crown and lining resistance are used to help the self-stabilization of the rock and the support.

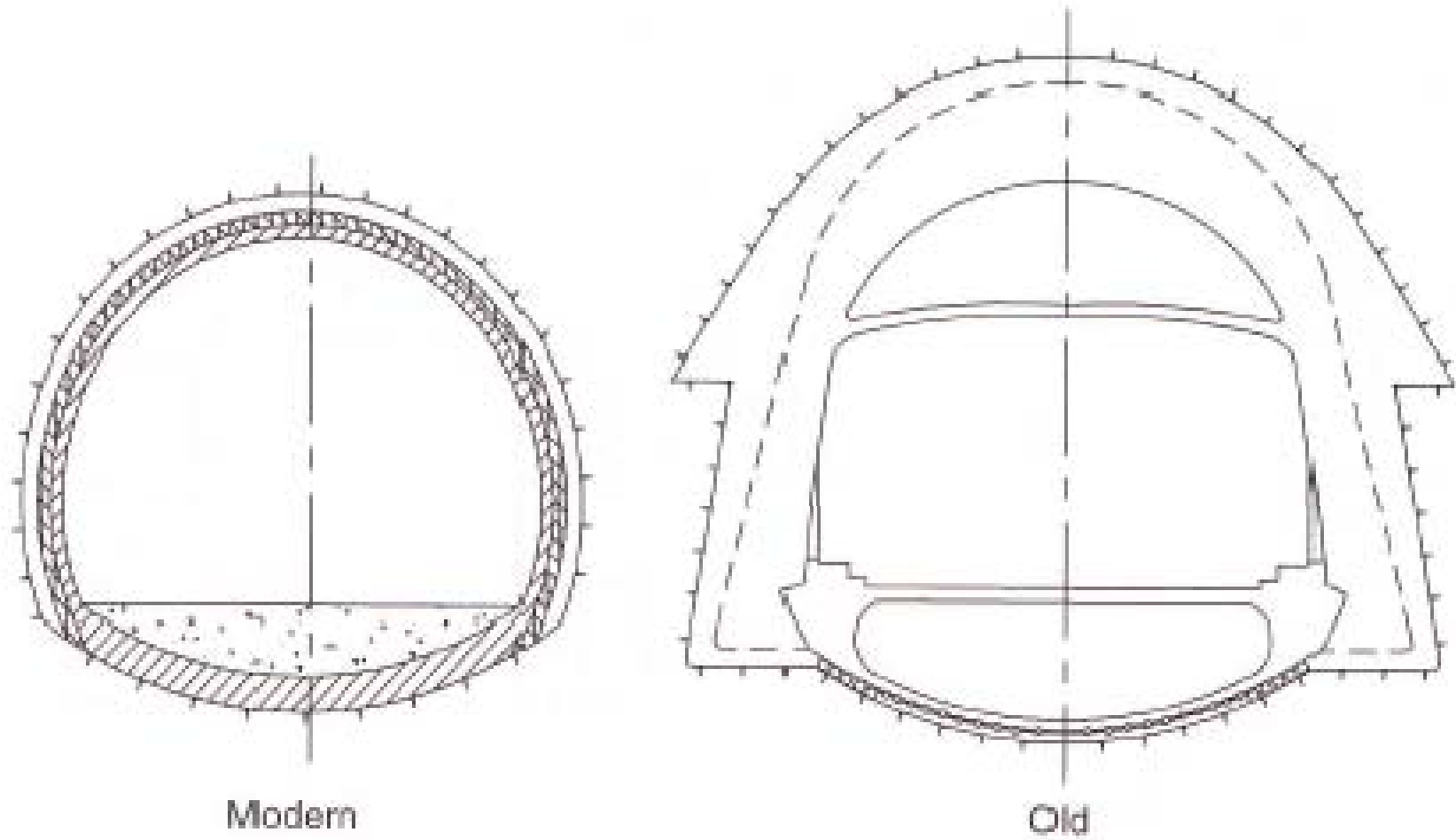


Fig. 9.15 Smoothly rounded shapes help to prevent stress concentrations.

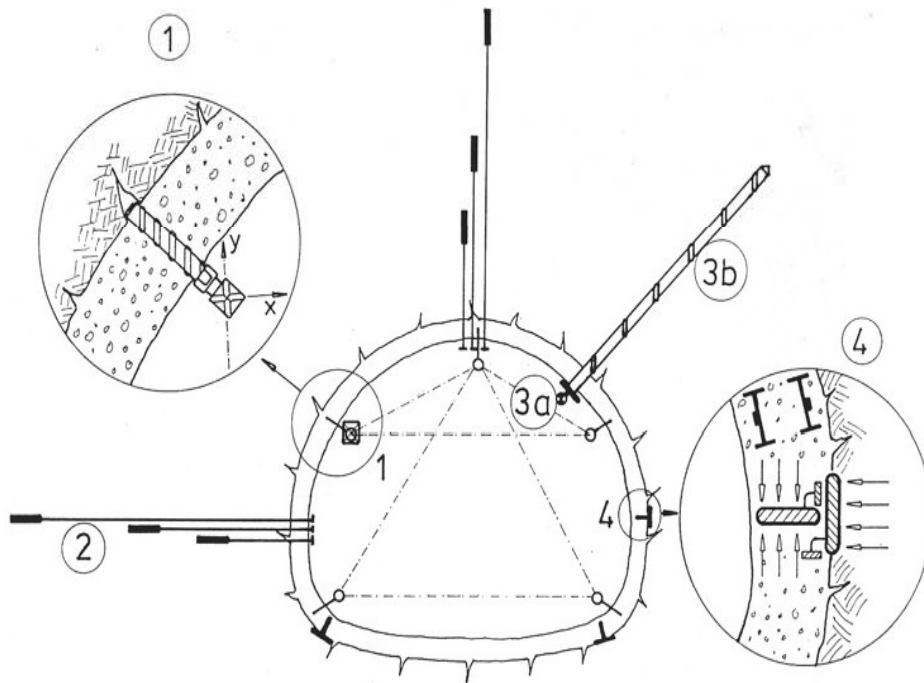
*The concept of NATM is to control deformations and stress rearrangement process in order to obtain a required safety level. Requirements differ depending on the type of project in a subway project in built up areas stability and settlements may be decisive, in other tunnels stability only may be observed. The NATM method is universal, but particularly suitable for irregular shapes. It can therefore be applied for underground transitions where a TBM tunnel must have another shape or diameter.*



## Observations of tunnel behaviour

- One of the most important factors in the successful application of observational methods like NATM is the observation of tunnel behaviour during construction. *Monitoring and interpretation* of deformations, strains and stresses are important to optimise working procedures and support requirements, which vary from one project to the other. In-situ observation is therefore essential, in order to keep the possible failures under control.
- Considerable information related to the use of instruments in monitoring soils and rocks are available from instrument manufacturers.

# Example measurement instrumentation in a tunnel lined with shotcrete.



1. Deformation of the excavated tunnel surface/  
Convergence tape  
Surveying marks
2. Deformation of the ground surrounding the tunnel/  
Extensometer
3. Monitoring of ground support element 'anchor'/  
Total anchor force
4. Monitoring of ground support element 'shotcrete shell'/  
Pressure cells  
Embedments gauge

## NATM Process on site

- Cutting a length of tunnel here with a roadheader



# Applying layer of shotcrete on reinforcement mesh



Primary lining applied to whole cavity, which remains under observation.



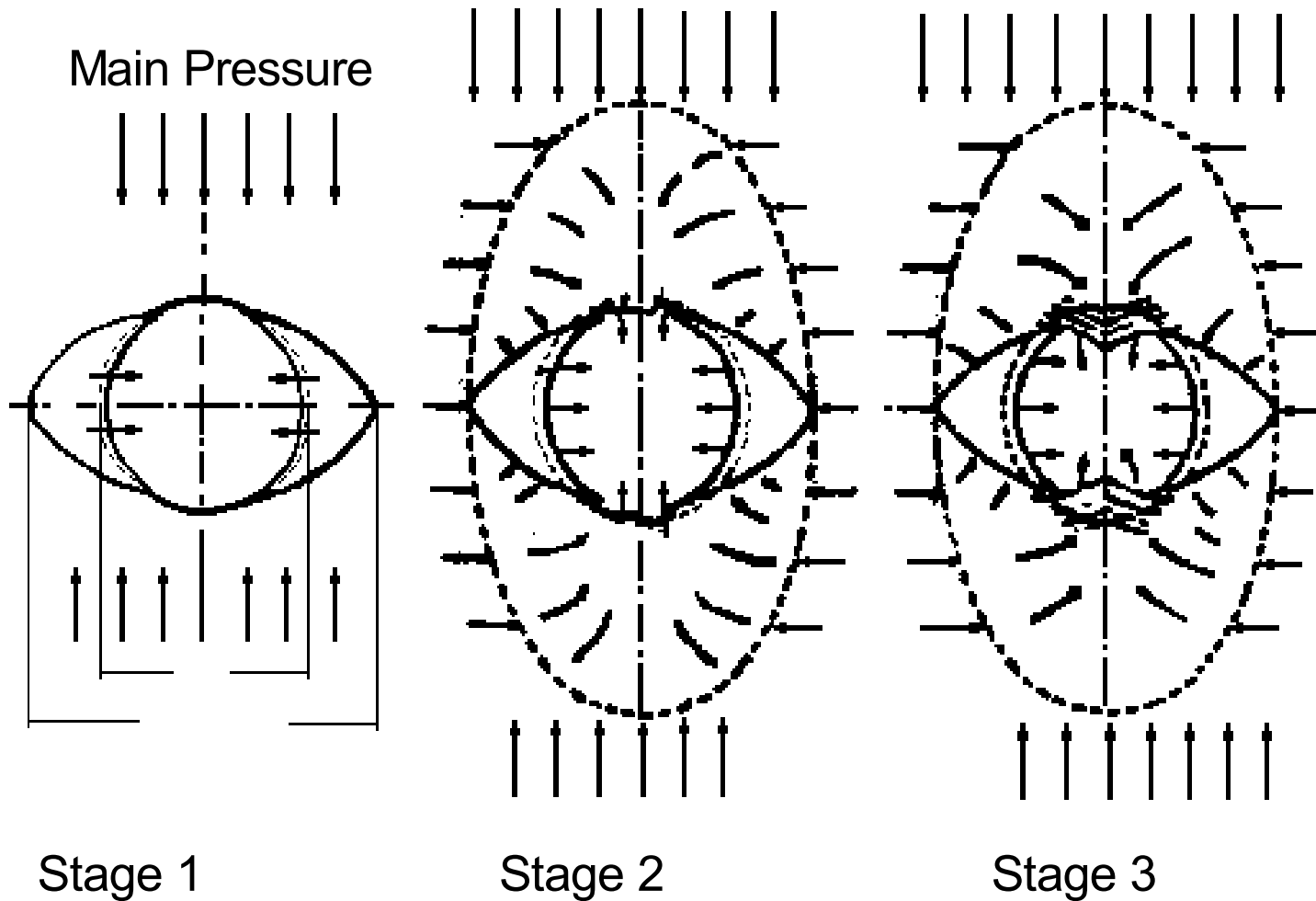
Final lining applied. Running tunnels continued.



# Completed underground transition

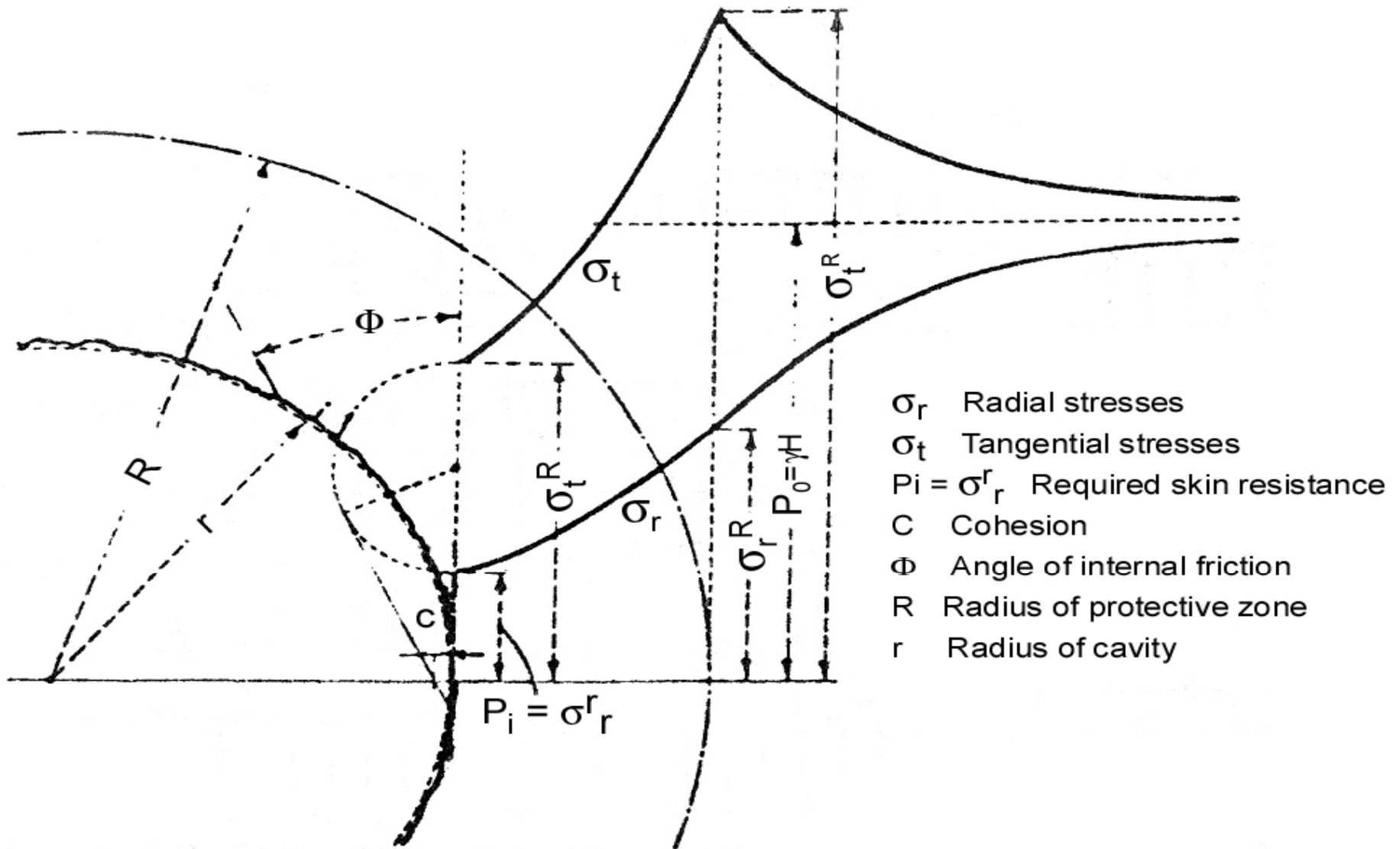


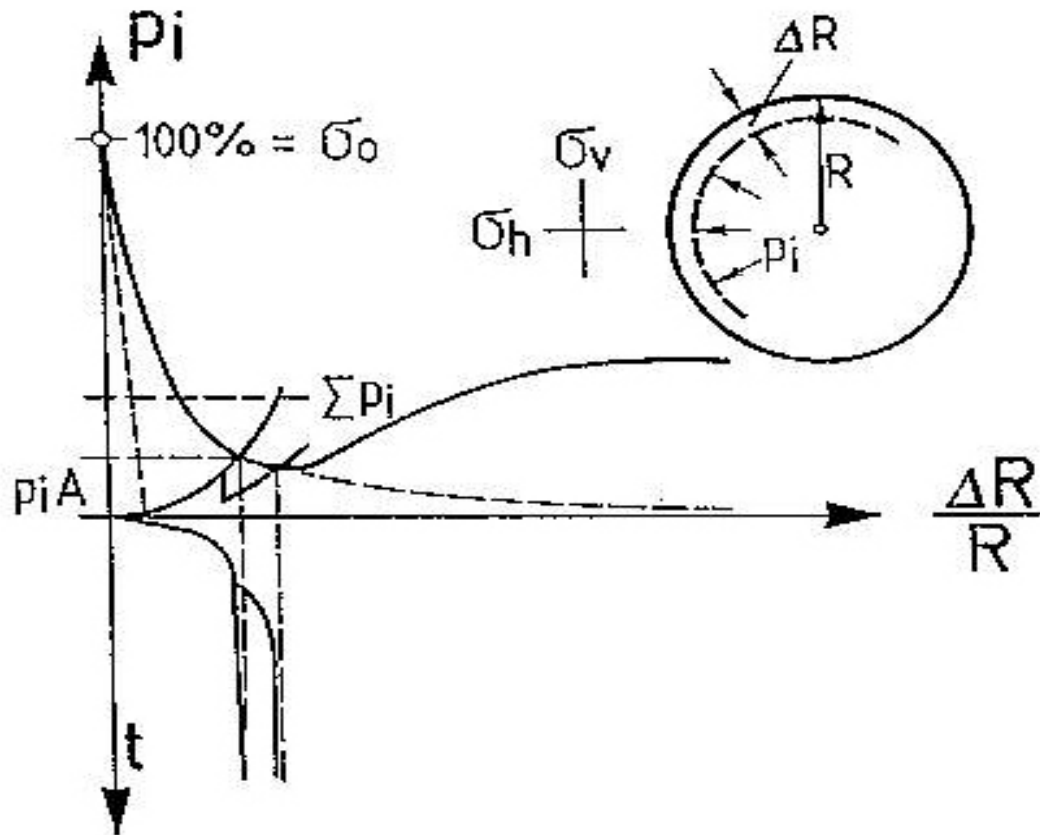
# Sketch of mechanical process and sequence of failure around a cavity by stress rearrangement pressure





# Schematic representation of stresses around a circular cavity with hydrostatic pressure





- The Fenner-Pacher curve shows the relationship between the deformation  $\Delta R/R$  and required support resistance  $P_i$ . Simplistically, the more deformation is allowed, the less resistance is needed. In practice, the support resistance reaches a minimum at a certain radial deformation, and support requirements increase if deformations become excessive.
- Fenner-Pacher-type diagrams can be generated to help evaluate the support methods best suited to the conditions.

Skin resistance which counteracts the radial stresses forming around the cavity, becomes smaller in time, and the radius of the cavity decreases simultaneously. These relations are given by the equations of Fenner-Talobre and Kastner.

$$P_i = -c \operatorname{Cotg} \varphi + [c \operatorname{Cotg} \varphi + P_0 (1 - \operatorname{Sin} \varphi)] \left( \frac{r}{R} \right)^{\frac{2 \operatorname{Sin} \varphi}{1 - \operatorname{Sin} \varphi}}$$

**where;**

$P_i$  = skin resistance

$C$  = cohesion

$\varphi$  = angle of internal friction

$R$  = radius of the protective zone

$r$  = radius of the cavity

$P_0 = \gamma H$ ; overburden

Following the main principle of NATM, the protective ring around the cavity ( $R-r$ ), is a load carrying part of the structure. The carrying capacity of the rock arch is formulated as;

$$P_i^R = \frac{S \tau_R \operatorname{Cos} \varphi}{b / 2} - \frac{S \sigma_n^R \operatorname{Sin} \varphi}{b / 2}$$

where;

$P_i$  = resistance of rock arch ( $t/m^2$ )

$S$  = length of shear plane (m)

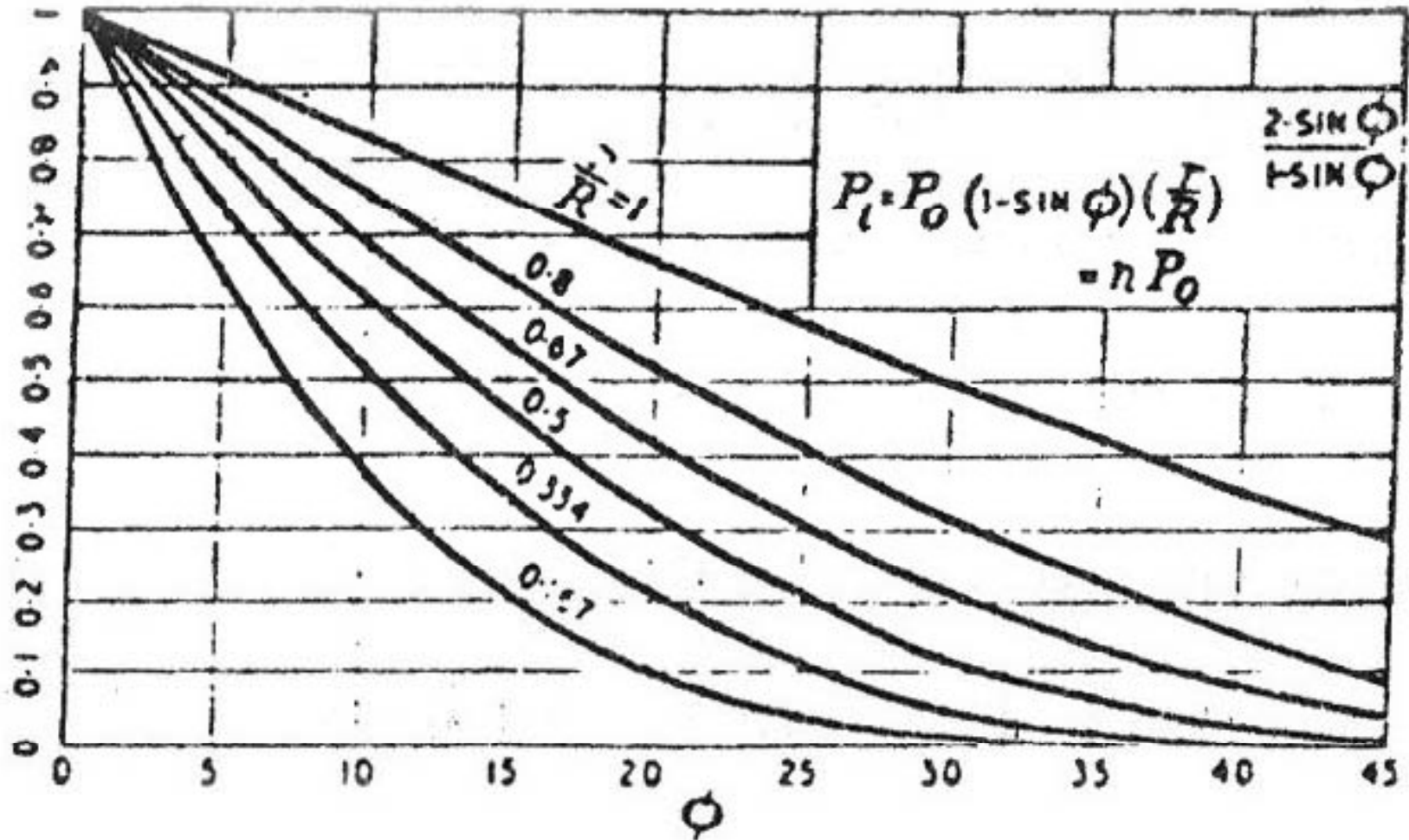
$\tau_R$  = shear strength of rock ( $t/m^2$ )

$\varphi$  = angle of internal friction (0)

$b$  = height of shear zone (m)

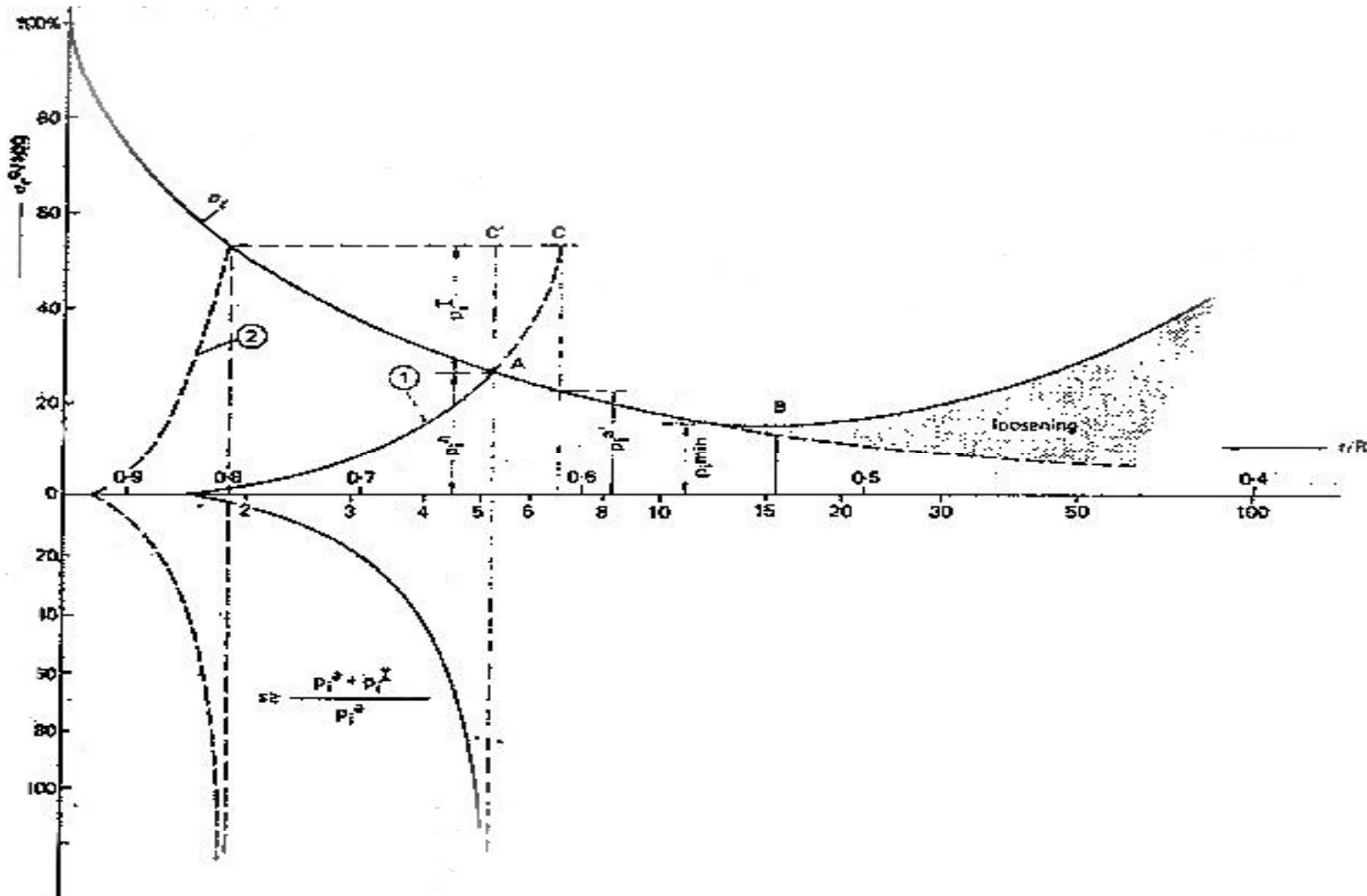
$\sigma_n^R$  = normal stress on shear plane ( $t/m^2$ )

$\phi$ ,  $\tau_R$ ,  $\sigma_n^R$ , can be measured in laboratories, where as  $S$  can be measured in meters , on a drawing made to scale.



- Generally two separate supports are carried out. The first is a flexible outer arch or protective support designed to stabilize the structure accordingly. It consists of a systematically anchored rock arch with surface protection, possibly reinforced by ribs and closed by an invert.
- The behaviour of the protective support and the surrounding rock during the readjustment process can be monitored by a measuring system.

The second means of support is an inner concrete arch, generally not carried out before the outer arch has reached equilibrium. In addition to acting as a final, functional lining (for installation of tunnel equipment etc.) its aim is to establish or increase the safety factors as necessary.



- The resistance of the lining material (shotcrete) is:

$$P_t^s = \frac{d \tau^s}{\sin \alpha^s (b / 2)}$$

- An additional reinforcement (steel ribs, etc.) gives a resistance of:

$$P_i^{st} = \frac{F^{st} \tau^{st}}{\sin \alpha^s (b / 2)}$$

- where;

$$\tau^{st} = \frac{\tau^s E^{st}}{E^s} = 15\tau^s$$

- The lining resistance is:

$$P_i^L = P_i^s + P_i^{st}$$

- The anchors are acting with a radial pressure:

$$P_i^A = \frac{f^{st} \sigma_p^{st}}{et}$$

- With the lateral pressure given by:

$$\sigma^3 = p_i^s + p_i^{st} + p_i^A$$

and with Mohr's envelope, the shear resistance of the rock mass  $\tau_R$  and the shear angle  $\alpha$  is determined, assuming that the principal stresses are parallel and at right angles to the excavation line.



The carrying capacity of the rock arch is given by:

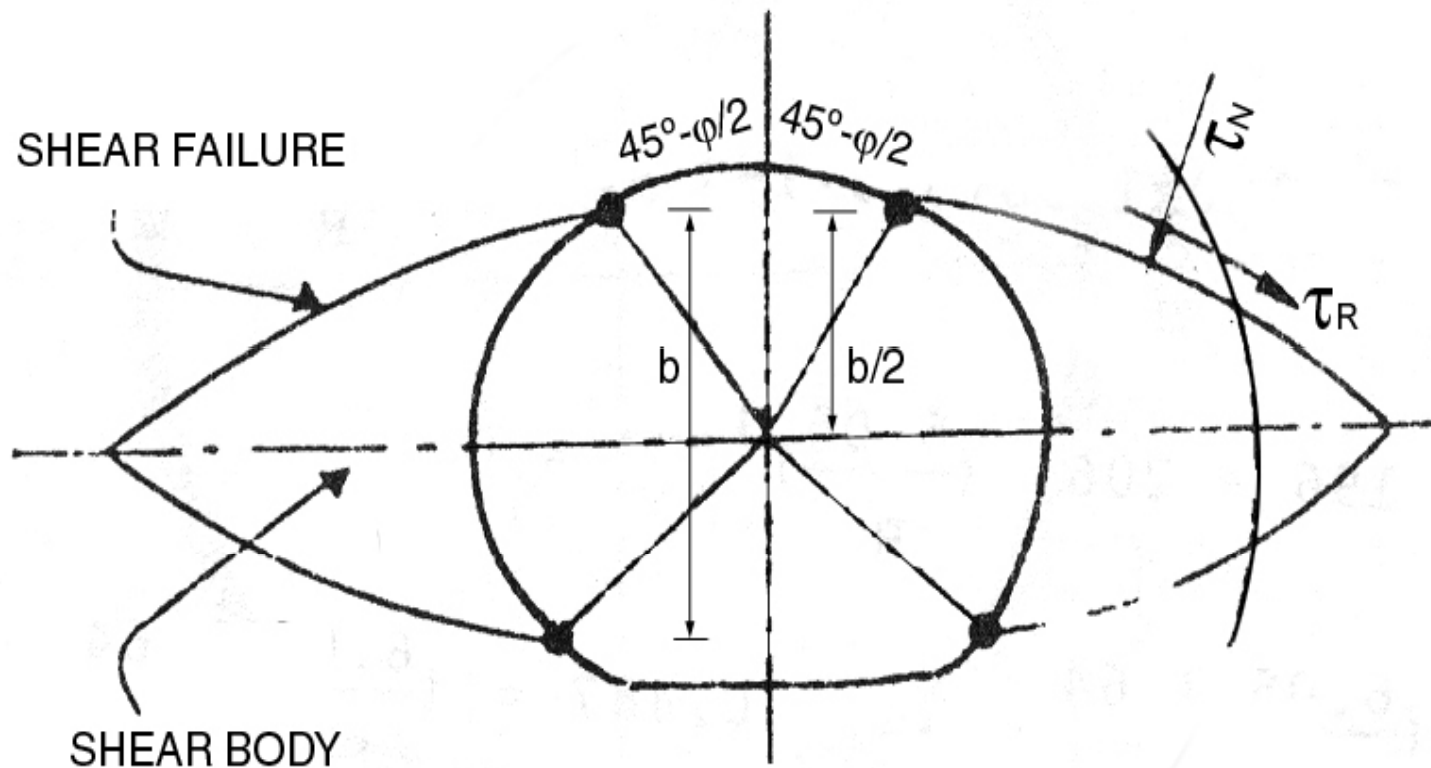
$$P_i^R = \frac{S \cdot \tau^R \cos \varphi}{b/2} - \frac{S \cdot \sigma_n^R \sin \varphi}{b/2}$$

The resistance of the anchors against the movement of the shear body towards the cavity is:

$$P_i^A = \frac{af^{st} \cdot \sigma_p^{st} \cos \beta}{et(b/2)}$$

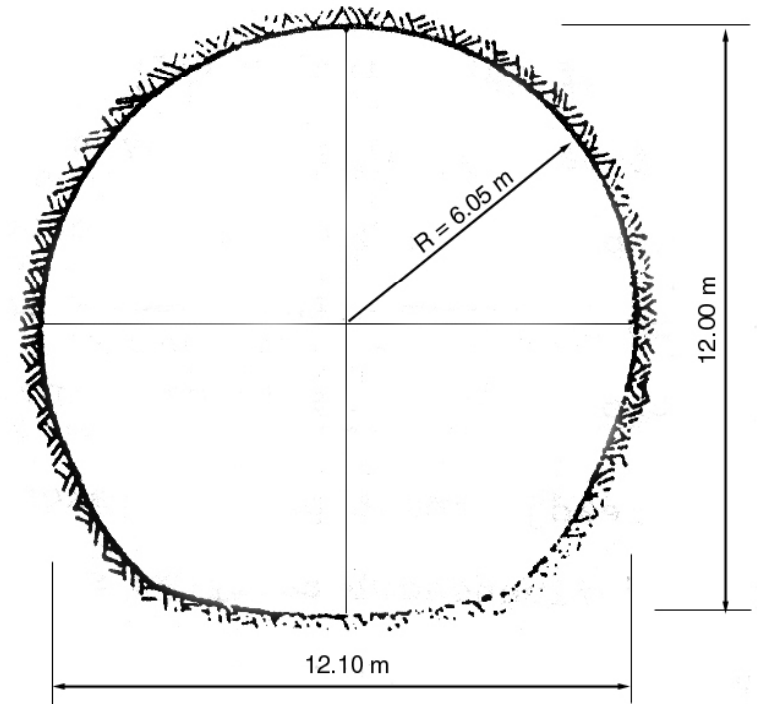
- The total carrying capacity of the outer arch is then:

$$P_i^w = P_i^L + P_i^R + P_i^A \geq P_{i \min}$$



## Numerical example for NATM

- Tunnel size: 12.10 x 12.00 m (fig.10)
- $H = 15.0$  m overburden according to tests on samples found:  $\phi = 27^\circ$ ,  $c = 100$  t/m<sup>2</sup> (three axial tests). When we open a cavity the stress equilibrium spoiled and for establishing new equilibrium condition achieved by supporting as follows.
- Use the supporting ring which develops around the cavity after excavation as a self-supporting device and select a type of supporting which can bear the developed rock loads and deformable when necessary.
- Design the inner lining under final loads



The (1) supporting system is capable of carrying safely the loads, the (2) lining is for safety and to bear the additional loads which are probable to develop after the supports are installed.

Supporting will consists in this example:

**a:** Shotcrete (15+10) cm in layers by two shots

**b:** Bolts spaced 2.00 x 2.00 m in rings with diameter Ø 26 mm.

**c:** Rib steel channel supports (2 x 14)

**d:** by ground supporting ring

To find the radius of disturbed zone R:

Talobre formula:

$$P_i = -c \cdot \cotg\varphi + \left[ c \cdot \cotg\varphi + P_0 \cdot (1 - \sin\varphi) \right] \cdot \left( \frac{r}{R} \right)^{\frac{2\sin\varphi}{1-\sin\varphi}}$$

Values entered into the formula:

$$\varphi = 27^\circ$$

$$\gamma = 2.5 \text{ t/m}^3$$

$$H = 15.0 \text{ m}$$

$$P_0 = \gamma H = 2.5 \times 15.0 = 37.5 \text{ t/m}^2$$

$$C = 100 \text{ t/m}^2$$

$$R = 6.45 \text{ m}$$

$$P_i = -100 \times \cot g 27^\circ + \left[ 100 \times \cot 27^\circ + 37.5 \times (1 - \sin 27^\circ) \right] \times \left( \frac{6.05}{R} \right)^{\frac{2 \sin 27}{1 - \sin 27}}$$
$$P_i = -100 \times 1.96 + \left[ 100 \times 1.96 + 37.5 \times (1 - \sin 27^\circ) \right] \times \left( \frac{6.05}{R} \right)^{\frac{2 \times 0.450}{1 - 0.450}}$$

$$-196.3 + 217.08 \times \left( \frac{6.05}{R} \right)^{1.66} = 0$$

$$\frac{196.3}{217.08} = \left( \frac{6.05}{R} \right)^{1.66}$$

$$R = 6.45 \text{ m}$$

## Shotcrete:

$$d = 25 \text{ cm}$$

$\sigma_c^{28} = 160 \text{ kg/cm}^2$  compressive strength shear in concrete (assume 20% of  $\sigma_c^{28}$ )

the capacity carrying load

$$\tau_s^h = 0.20 \cdot 160 = 32 \text{ kg/cm}^2 = 320 \text{ t/m}^2$$

$d$  = thickness of shotcrete in (cm)

$\alpha = \pi/4 - \varphi/2$  angle of shear plane with vertical

$b$  = shear failure height of the cavity (see Fig.10)

$$\sin 31.5 = 0.520;$$

$$b/2 = r \cos \alpha = 6.05 \times \cos 31.5 = 5.15$$

$$p_i^c = \frac{0.25 \cdot 320}{0.52 \cdot 5.15} = 29.9 \text{ t/m}^2$$

## bolts

Bolt Ø 26 mm

St III,  $\sigma_s^h = 4000 \text{ kg/cm}^2$

Spacing=2x2 m

$f = 5.3 \text{ cm}^2$

$$p_i^b = \frac{5.3 \cdot 4000}{200 \cdot 200} = 0.53 \text{ kg/cm}^2$$

$$p_i^b = 5.3 \text{ t/m}^2$$

## steel ribs

t = spacing 2.00 m

$$F = 2 \cdot 20.4 \text{ cm}^2 = 40.8 \text{ cm}^2 = 0.00408 \text{ m}^2$$

$$\tau_{st} = \tau_c \cdot 15 = 320 \cdot 15 = 4800 \text{ t/m}^2$$

$$P_i^{st} = \frac{F \cdot \tau_{st}}{\sin \alpha \cdot \frac{b}{2} \cdot t} = \frac{0.00408 \cdot 4800}{0.52 \cdot 5.15 \cdot 2.00} = 36.56 \text{ t/m}^2$$

Connect AB and find the centre (W) draw the circle. Tangent at the point B (BB') so

OB' = Cohesion = 100 t/m<sup>2</sup>

φ = internal friction angle (27°)

R calculated (Talobre formula) as 6.45 m. Width of the protective ring 6.45-6.05 = 0.4m drawn through A, B and the intersection bisecting with the middle ring (C); ABC shear failure line drawn and thus (S) measured.

Bolt length l = 4.00 m is taken and inclination β measured

$$\Sigma P_i = p_i^c + p_i^b + p_i^{st} = 29.9 + 5.3 + 36.56 = 70.26 \text{ t/m}^2$$

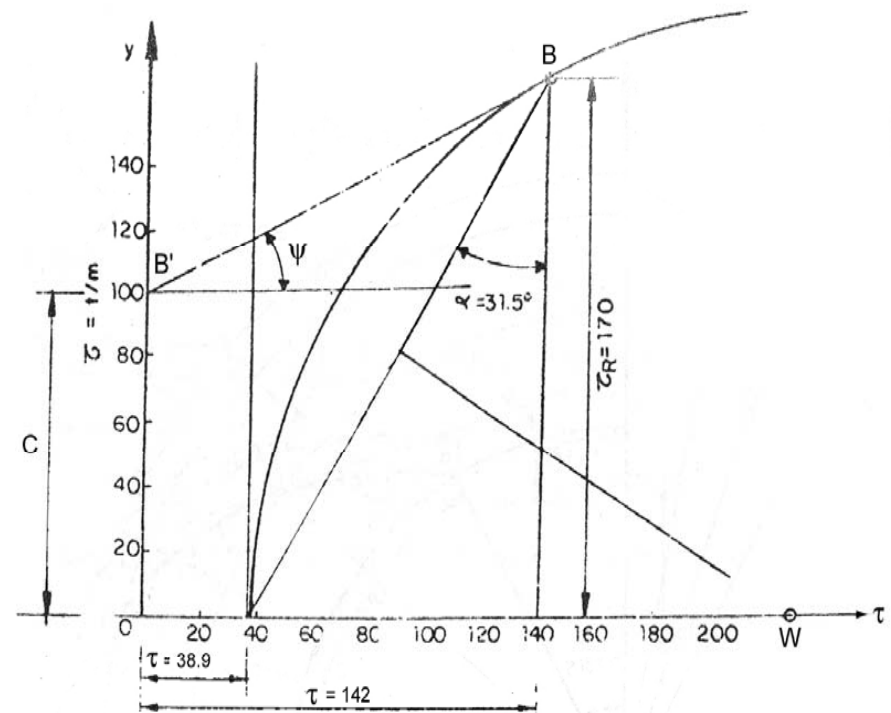
$$\tau_N = \text{normal stress} = 142 \text{ t/m}^2$$

$$\tau_Z = \text{minor stress} = 37.2 \text{ t/m}^2$$

$$\tau_R = \text{shear stress} = 170 \text{ t/m}^2$$

read on X

read on Y





## bearing capacity of the supporting ring

$$\sin \varphi = \sin 27 = 0.450$$

$$\cos \varphi = \cos 27 = 0.891$$

thus

$$S = 4.54 \text{ m (from figure 17)}$$

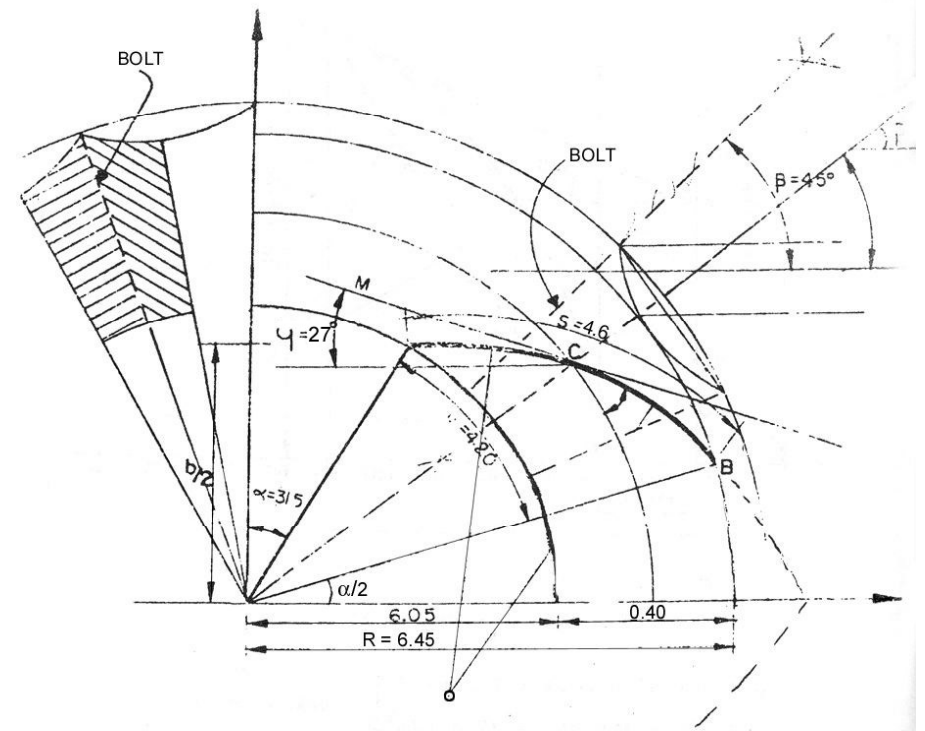
$$\varphi = 27^\circ$$

$$b/2 = 5.15 \text{ m}$$

$$\tau R = 170 \text{ t/m}^2$$

$$\tau N = 142 \text{ t/m}^2$$

enter the formula



$$p_C^R = \frac{4.6 \cdot 170 \cdot 0.891}{5.15} - \frac{4.6 \cdot 142 \cdot 0.450}{5.15}$$

$$p_C^R = 78.22 \text{ t/m}^2$$

The resistance of the bolts (anchors) against the movement of the shear body towards the cavity is:

$$p_i^{\bar{b}} = \frac{a \cdot f \cdot \sigma_{sh} \cdot \cos \beta}{e \cdot t \cdot b / 2}$$

( $b/2$ ,  $a = 4.20$  m,  $\beta = 35.5^\circ$  from Fig 17)

$$p_i^{\bar{b}} = \frac{4.20 \cdot 5.20 \cdot 4000 \cdot 0.81}{2.00 \cdot 2.00 \cdot 5.15} = 3.43 \text{ t/m}^2 < 5.3 \text{ t/m}^2$$

$\sigma_{\text{shear}} = 4000 \text{ kg/cm}^2$  ;  $e \cdot t_1 = \text{bolts arrangement} = 2.00 \cdot 2.00 \text{ m}$

So the total bearing capacity of supporting will be

$$P_i = P_i^c + P_i^b + P_i^{\text{st}} + P_i^R = 29.9 + 3.43 + 36.56 + 78.22 = 160.1 \text{ t/m}^2$$