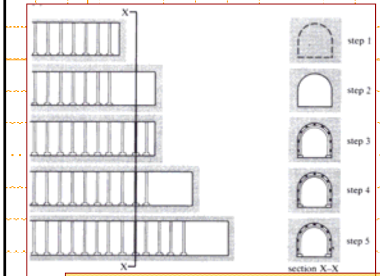
EOSC 547:

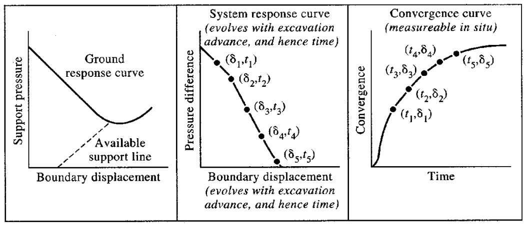
Tunnelling & Underground Design

Topic 5:
Tunnelling in Weak Rock – Sequential Excavation

Ground Reaction – Convergence

In practice, it may not be possible to establish the exact form of the ground response curve, but we can measure the displacement that occurs, usually in the form of convergence across an excavation. The ground response curve and convergence curves are linked because they are different manifestations of a single phenomenon.



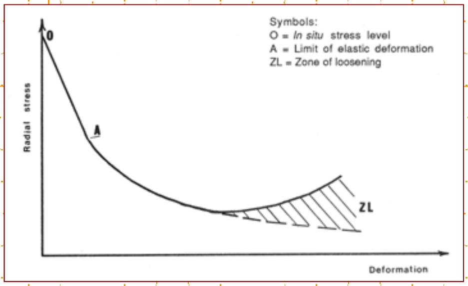


Hudson & Harrison (1997)

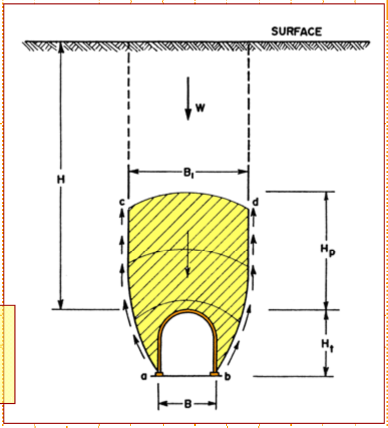
Convergence occurs rapidly as excavation proceeds; subsequently the convergence rate decreases as equilibrium is approached. This leads directly to the New Austrian Tunnelling Method (NATM), a type of observational method.

Ground Reaction – Convergence

As demonstrated with the ground response curve, a key principle in rock tunnelling is the recognition that the main component of tunnel support is the strength of the rock mass and that it can be mobilized by minimizing deformations and preventing rock mass "loosening".



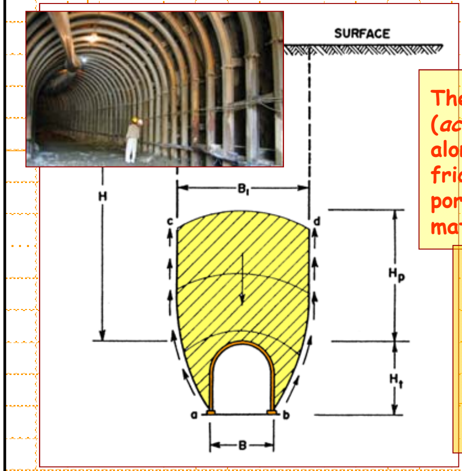
Whittaker & Frith (1990)



During construction of a tunnel, some relaxation of the rock mass will occur above and along the sides of the tunnel.

Terzaghi's Rock Load

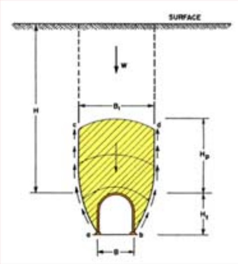
Terzaghi (1946) formulated the first rational method of evaluating rock loads appropriate to the design of steel sets.

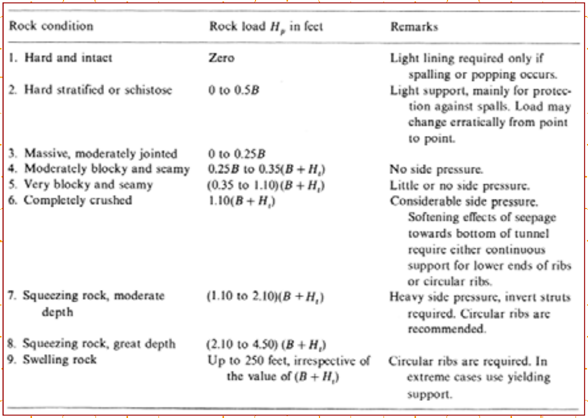


The movement of the loosened area of rock (*acdb*) will be resisted by friction forces along its lateral boundaries and these friction forces help to transfer the major portion of the overburden weight onto the material on either side of the tunnel.

As such, the roof and sides of the tunnel are required only to support the balance which is equivalent to a height H_p. Terzaghi related this parameter to the tunnel dimensions and characteristics of the rock mass to define a series of steel arch support guidelines.

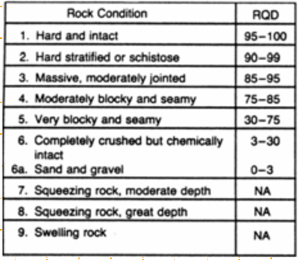
Terzaghi's Rock Load





Rock condition	Rock load H_p in feet	Remarks
1. Hard and intact	Zero	Light lining required only if spalling or popping occurs.
2. Hard stratified or schistose	0 to $0.5B$	Light support, mainly for protection against spalls. Load may change erratically from point to point.
3. Massive, moderately jointed	0 to $0.25B$	
4. Moderately blocky and seamy	$0.25B$ to $0.35(B+H_t)$	No side pressure.
5. Very blocky and seamy	$(0.35$ to $1.10)(B+H_t)$	Little or no side pressure.
6. Completely crushed	$1.10(B+H_t)$	Considerable side pressure. Softening effects of seepage towards bottom of tunnel require either continuous support for lower ends of ribs or circular ribs.
7. Squeezing rock, moderate depth	$(1.10$ to $2.10)(B+H_t)$	Heavy side pressure, invert struts required. Circular ribs are recommended.
8. Squeezing rock, great depth	$(2.10$ to $4.50)$ $(B+H_t)$	
9. Swelling rock	Up to 250 feet, irrespective of the value of $(B+H_t)$	Circular ribs are required. In extreme cases use yielding support.

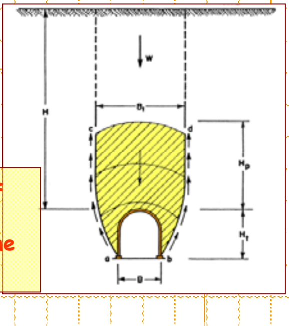
Terzaghi (1946)



Rock Condition	RQD
1. Hard and intact	95–100
2. Hard stratified or schistose	90–99
3. Massive, moderately jointed	85–95
4. Moderately blocky and seamy	75–85
5. Very blocky and seamy	30–75
6. Completely crushed but chemically intact 6a. Sand and gravel	3–30 0–3
7. Squeezing rock, moderate depth	NA
8. Squeezing rock, great depth	NA
9. Swelling rock	NA

Deere *et al.* (1970)

Tunnelling in Weak Rock



Terzaghi's "Rock Load" implicitly relates the benefits gained through the grounds natural tendency to arch. The essence of tunnelling in many respects is to disturb the natural arch as little as possible while excavating the material.

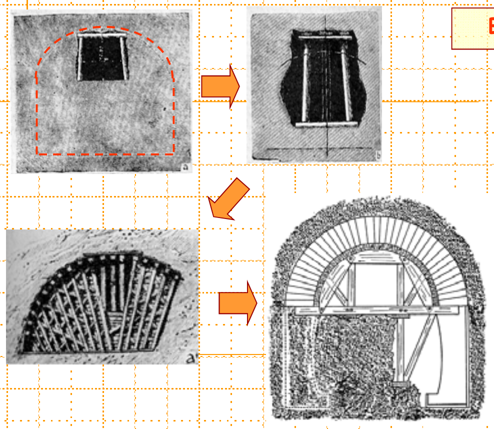
In weak rock, ground loosening breaches the integrity of this natural arch. The consequence is that without supporting the excavation soon after it is completed – the walls may squeeze together and the roof may fall in.

Besides the strength of the rock mass, a second key factor controlling the extent of loosening is the size of the excavation. Several difficulties relating to the size of the face include:

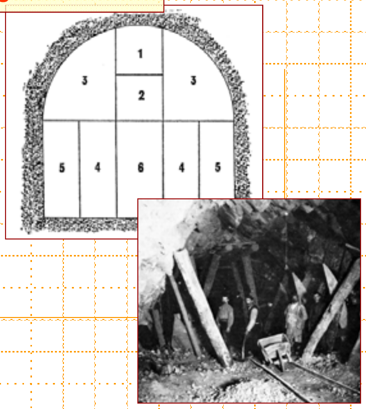
- increased volume of ground disturbed
- decreased accessibility to all parts of the face
- increasing difficulty in supporting and controlling face stability

Early Tunnel Experiences in Weak Rock

Through much trial and error, the lesson commonly learned was that with a small tunnel face, the volume of ground moving and relaxing is also smaller and can often be tolerated or kept within acceptable limits by relatively simple timbering or other temporary support.

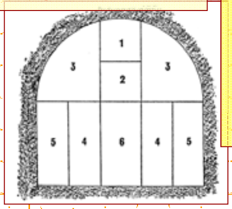


Belgium method



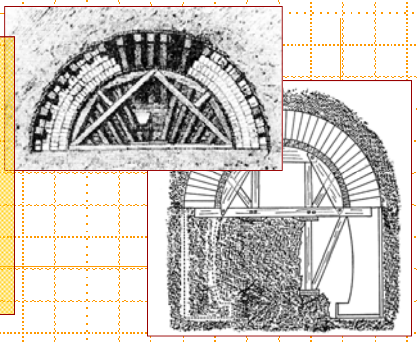
Early Tunnel Experiences in Weak Rock

Belgium method



The Belgium method was first employed in building the Chaleroy tunnel (in Belgium) in 1828. The great advantage claimed for the system by Belgian and French engineers was the speed whereby the roof of the tunnel could be secured, a desirable advantage in poor rock.

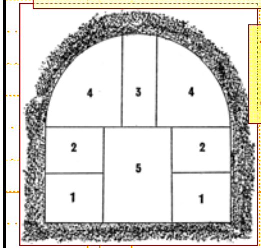
The method fell out of favour as a result of catastrophic experiences encountered during the construction of the Gotthard Tunnel (1872-1882). The key problem was that the sequencing following Stage 3 required the arch to be underpinned. However, this proved difficult in the yielding ground conditions encountered, leading to the timbers giving way, followed by the cracking or total collapse of the masonry arch.



Beaver (1972)

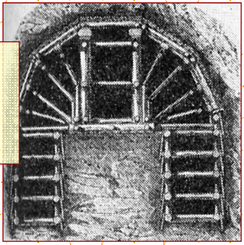
Early Tunnel Experiences in Weak Rock

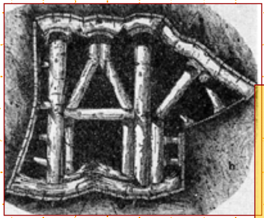
German system



The underlying principle of the "German System" was to leave a central bench of ground to be excavated last and to use it to support roof and wall timbering.

This allowed the arching to be built in one operation (unlike the Belgium method which had the disadvantage of building the arch and walls separately).

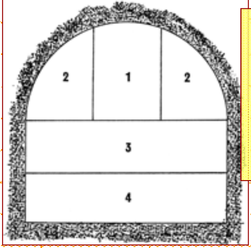




The German system came to a disastrous end when applied to the Cžernitz tunnel in Austria (1866), where the timbers supporting the heading either pushed into the core, whereupon they became loose, or were crushed by swelling pressures that developed in the core.

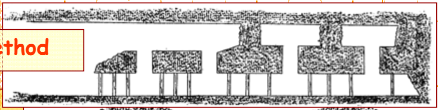
Early Tunnel Experiences in Weak Rock

English Method

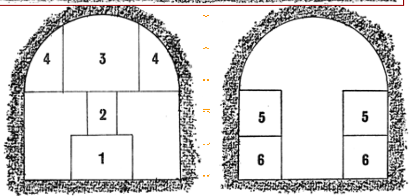


This method was used to tunnel through clay, shale and sandstones. The great advantage of the method was that the masonry was built in one piece from foundation to arch, resulting in a strong homogeneous construction. It's drawback was that tunnellers and masons had to work in turn, making the method the most expensive of all.

Upraise Method



The method involved first excavating a lower heading. Vertical upraises were then excavated from which the top heading was driven leaving a dividing floor. After the top heading was enlarged to form an arch, the dividing floor was removed and the lower heading broken out to full size.

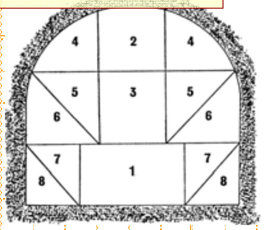


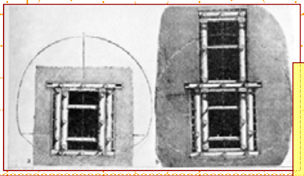
Beaver (1972)

Early Tunnel Experiences in Weak Rock

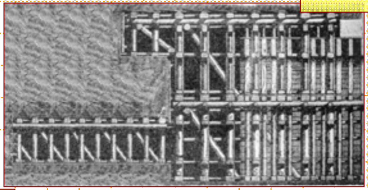
The "Old" Austrian Tunnelling Method was first used for the Oberau tunnel in 1837, which was constructed through marls, gneiss and granite. The method resembles the English method in that the full section was excavated before the masonry was added. The key difference was that excavation was carried out in small sections.

Austrian method





A centre-bottom heading was first driven for a distance of about 5 m. This 'pilot tunnel' served to ventilate the workings, to drain the surrounding area, and aided in establishing the tunnel alignment.

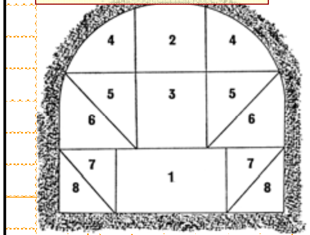


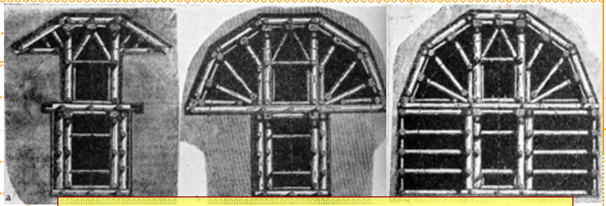
A centre-top heading then followed (driven for the same distance). Section 3 was then removed by men working from the top heading, enabling the top structures to rest on the undisturbed timbers below.

Sandström (1963)

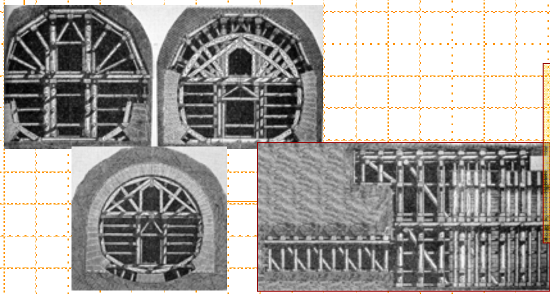
Early Tunnel Experiences in Weak Rock

Austrian method





Breaking out of the tunnel to full width then began at the shoulders, working down.

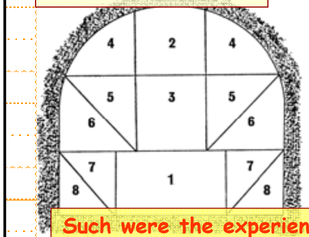


Once the excavation was fully opened, the masonry lining was built up from the foundations to the crown of the arch in consecutive 5 m long sections.

Sandström (1963)

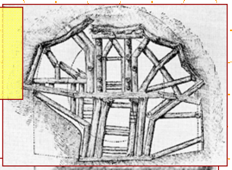
Early Tunnel Experiences in Weak Rock

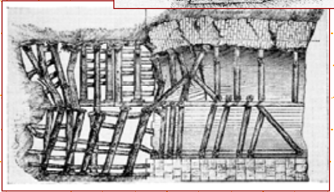
Austrian method



An important aspect of this method was that the driving of a large number of headings, which were immediately strutted, allowed for minimal disturbance of the surrounding ground. The main disadvantage was that the strutting was liable to distort or give way under asymmetrical pressures.

Such were the experiences with the Christina Tunnel in Italy (1865-70), sometimes referred to as the "most dreadful underground construction ever undertaken".



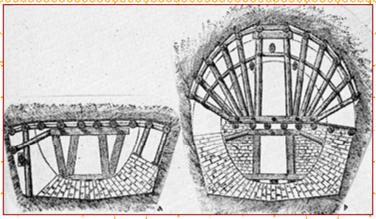


The material through the tunnel was driven consisted of a peculiar type of clay that lacked cohesion. When the clay beds were disturbed by the excavation, the clay would slide along laminations. Swelling also gave trouble at the sides and bottom, necessitating the removal of much additional material. At times, the excess swelled to 4x the tunnel area!!

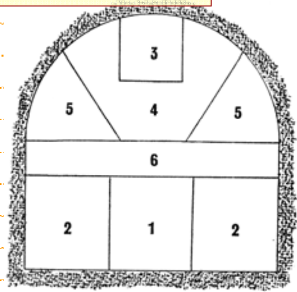
Sandström (1963)

Early Tunnel Experiences in Weak Rock

To deal with the soft soil, the bottom half of the tunnel was excavated first, a short section at a time, and a heavy stone invert was installed in order to get solid support for excavating and lining the top half.



Italian System

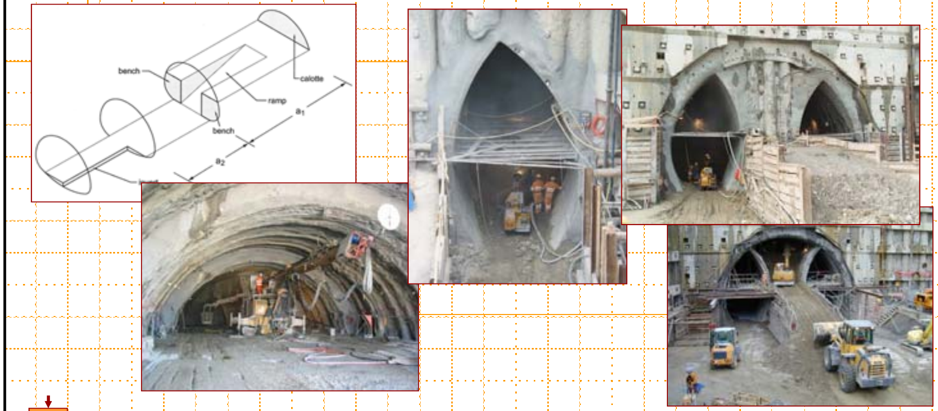


Beaver (1972)

This system (building a lower arch first and filling it with masonry) was dubbed the Italian System. However, no records of applying this system to other tunnels exists. Today, such poor or 'running' ground conditions would be pre-treated using freezing or by chemical means.

Sequential Excavation Methods (SEM)

Although the use of these early systems eventually died out due to the huge quantity and high cost of timber required, and the replacement of masonry linings with concrete, their underlying principles still live on. That is the benefits of driving one or more small headings that are later enlarged, enabling for ground deformations to be controlled better.



The Observational Method in Design

In the 1940's, Karl Terzaghi introduced a systematic means to solve geotechnical problems in the face of geological uncertainty, referring to it as the "observational method" (paraphrased here):

> "In geotechnical engineering, a vast amount of effort goes towards securing *roughly approximate* values for required parameter inputs. Many additional variables are not considered or remain unknown. Thus, the results of computations are no more than *working hypotheses*, subject to confirmation or modification during construction."
>
> "These uncertainties require either the adoption of an *excessive factor of safety*, or else assumptions based on *general experience*. The first of these is wasteful; the second is dangerous as most failures occur due to unanticipated ground conditions."
>
> "As an alternative, the *observational method*, provides a 'learn as you go' appraoch. The procedure for this is to base the design on whatever information can be secured, making note of all possible differences between reality and the assumptions (i.e. worst case scenarios), and computing for the assumed conditions, various quantities that can be measured in the field. Based on the results of these measurements, gradually close the gaps in knowledge and, if necessary, *modify the design during construction*."

Terzaghi & Peck (1948)

The Observation Method in Design

In brief, the complete application of the method embodies the following components:

a) Sufficient exploration to establish the general nature, pattern and properties of the soil deposits or rock mass;

b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions;

c) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions;

d) Selection of quantities to be observed during construction and calculation of their anticipated values on the basis of the working hypothesis;

e) Calculation of values of the same quantities under the most unfavourable conditions compatible with the available subsurface data;

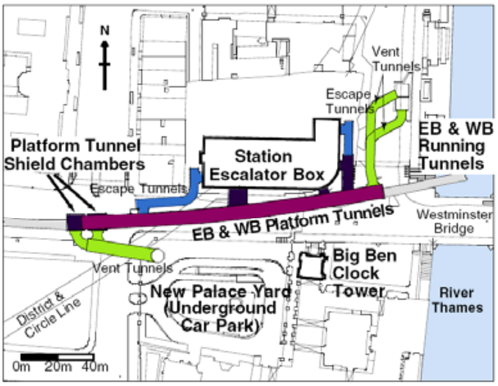
f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis;

g) Measurement of quantities to be observed and evaluation of actual conditions;

h) Modification of design to suit actual conditions.

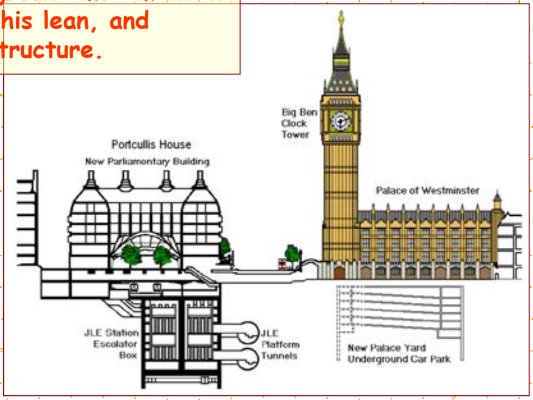
Observation Method Example – Jubilee Extension

The Jubilee Line Extension to the London Underground, started in 1994 and called for twin tunnels 11 km long, crossing the river in four places, with eleven new stations to be built, eight of which were to be underground. One of the more problematic of these was a station placed right opposite Big Ben.



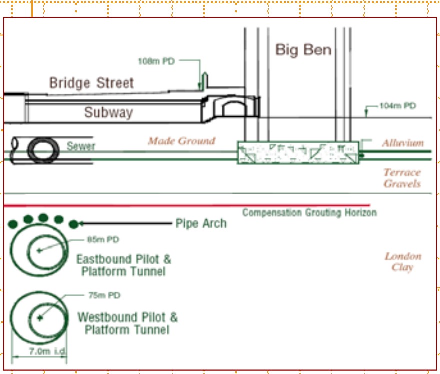
Observation Method Example – Jubilee Extension

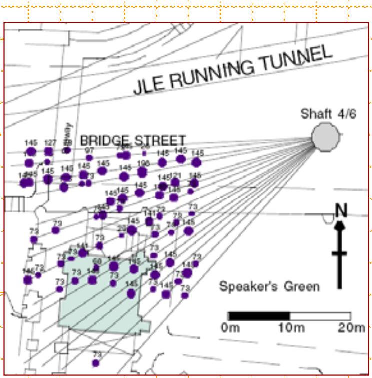
The technical implications were immense. Built in 1858, Big Ben is known to be on a shallow foundation. It started to lean towards the North shortly after completion. Any ground movement in the vicinity would exaggerate this lean, and threaten the stability of the structure.



Observation Method Example – Jubilee Extension

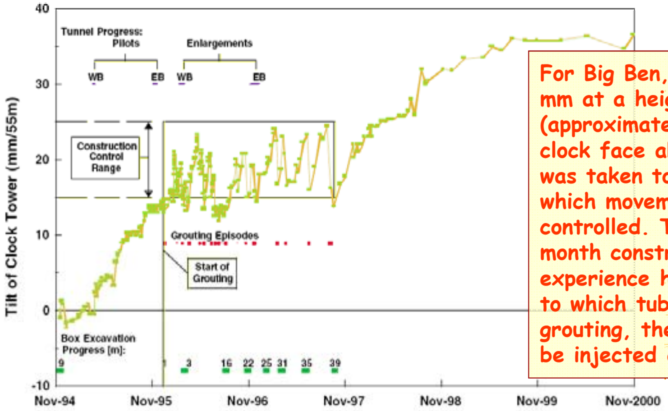
To deal with excavation-induced settlements that may irreversibly damage historic buildings in the area, the design called for the use of compensation grouting during tunnelling. In this process, a network of horizontal tubes between the tunnels and the ground surface is introduced, from which a series of grout holes are drilled. From these, liquid cement can be injected into the ground from multiple points to control/prevent movement during excavation of the main tunnels.





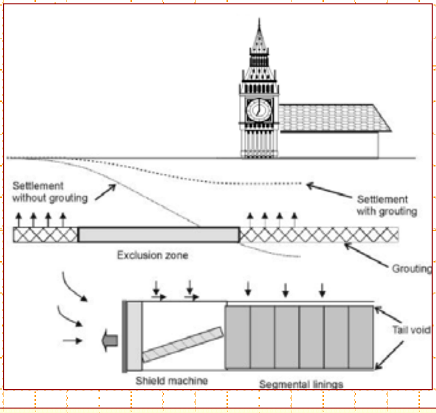
Observation Method Example – Jubilee Extension

Instrumentation was attached to Big Ben and to the buildings in the vicinity to measure movement (with some 7000 monitoring points), and computers were used to analyze the data to calculate where and when the grout has to be injected.



For Big Ben, a movement of 15 mm at a height of 55m (approximately the height of the clock face above ground level) was taken to be the point at which movement had to be controlled. Throughout the 28 month construction period, experience had to be gained as to which tube to use for grouting, the volume of grout to be injected and at what rate.

Observation Method Example – Jubilee Extension



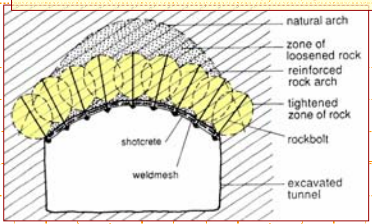
It was calculated that without the grouting, the movement of Big Ben would have gone well over 100 mm, which would have caused unacceptable damage.

Following construction, the grouting pipes were left in place and monitoring continued. Thus, compensation grouting can be restarted if required. However, instrumentation is showing that no further grouting is necessary.

Controlling Ground Deformations

In order to preserve the rock mass strength, by minimizing rock mass deformations, it is necessary to apply temporary support early. Temporary support measures may include steel sets, rock bolts, wire mesh and shotcrete. These temporary support measures are generally seen as the major load bearing component, with the primary concrete lining being erected after the tunnel has become stable. The primary role of this lining is to seal the tunnel and to provide a partial load bearing component.

Support is added to create a stable self-supporting arch within the rock mass over the tunnel opening.



Forepoling is used to provide an arching effect in the 3rd dimension to control ground deformations ahead of the tunnel face.

New Austrian Tunnelling Method (NATM)

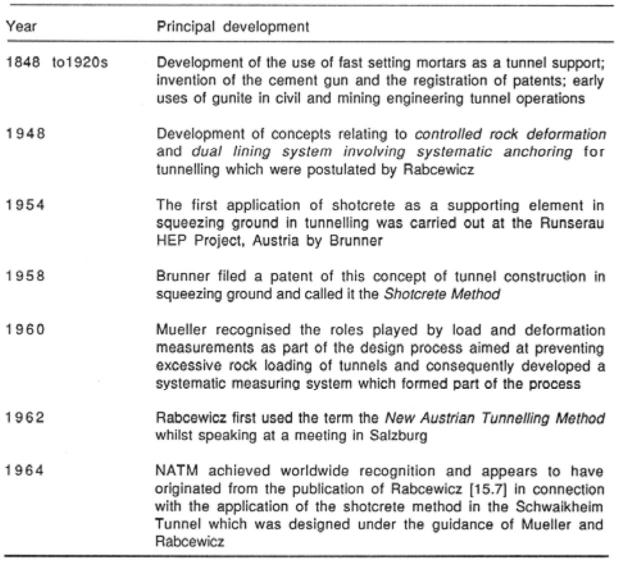
The New Austrian Tunnelling Method (NATM) is an approach or philosophy integrating the principles of rock mass behaviour and the monitoring of this behaviour during tunnel excavation. The word 'method' is a poor choice of word usage, as the NATM is not a set of specific excavation and support techniques. Instead, the NATM involves a combination of many established ways of excavation and tunnelling, but the difference is the continual monitoring of the rock movement and the revision of support to obtain the most stable and economical lining.

What the NATM is not:
- A method (i.e. a set of specific excavation and support guidelines).
- Simply the employment of shotcrete as support.

Rabcewicz (1964):

"A new tunnelling method – particularly adapted for unstable ground – has been developed which uses surface stabilisation by a thin auxiliary shotcrete lining, suitably reinforced by rockbolting and closed as soon as possible by an invert. Systematic measurement of deformation and stresses enables the required lining thickness to be evaluated and controlled".

New Austrian Tunnelling Method (NATM)

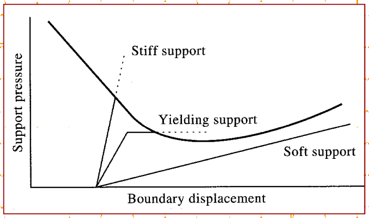


Year	Principal development
1848 to1920s	Development of the use of fast setting mortars as a tunnel support; invention of the cement gun and the registration of patents; early uses of gunite in civil and mining engineering tunnel operations
1948	Development of concepts relating to *controlled rock deformation* and *dual lining system involving systematic anchoring* for tunnelling which were postulated by Rabcewicz
1954	The first application of shotcrete as a supporting element in squeezing ground in tunnelling was carried out at the Runserau HEP Project, Austria by Brunner
1958	Brunner filed a patent of this concept of tunnel construction in squeezing ground and called it the *Shotcrete Method*
1960	Mueller recognised the roles played by load and deformation measurements as part of the design process aimed at preventing excessive rock loading of tunnels and consequently developed a systematic measuring system which formed part of the process
1962	Rabcewicz first used the term the *New Austrian Tunnelling Method* whilst speaking at a meeting in Salzburg
1964	NATM achieved worldwide recognition and appears to have originated from the publication of Rabcewicz [15.7] in connection with the application of the shotcrete method in the Schwaikheim Tunnel which was designed under the guidance of Mueller and Rabcewicz

Whittaker & Frith (1990)

Key Elements of the NATM Philosophy

1) **Mobilization of Strength:** The inherent strength of the soil/rock surrounding the tunnel should be conserved and mobilised to the maximum extent possible (i.e. controlled deformation of the ground is required to develop its full strength). Primary support is directed to enable the rock to support itself. It follows that the support must have suitable load-deformation characteristics and be placed at the correct time.

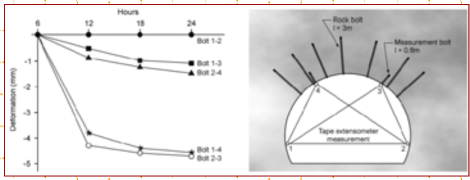


While the NATM generally includes shotcrete, it does not mean that the use of shotcrete constitutes the NATM.

2) **Primary Support:** Minimization of ground loosening and excessive deformations may be achieved in various ways, but generally a primary support system consisting of systematic rock bolting and a thin semi-flexible shotcrete lining is used. Whatever support is used, it is essential that it is placed and remains in physical contact with the ground and deforms with it.

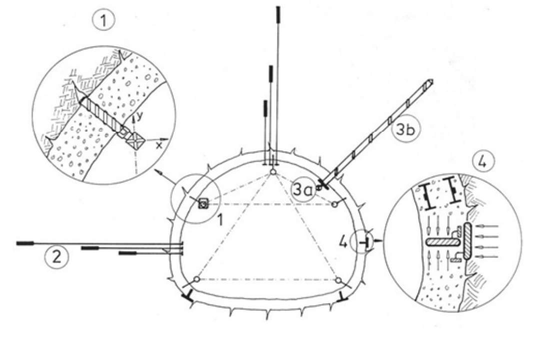
Key Elements of the NATM Philosophy

3) Flexible Support: The NATM is characterized by versatility/adaptability leading to flexible rather than rigid tunnel support. Thus strengthening is not by a thicker concrete lining but a flexible combination of rockbolts, wire mesh and steel ribs. The primary support will partly or fully represent the total support required and the dimensioning of the secondary support will depend on measurement results.



4) Measurements: The NATM requires the installation of instrumentation at the time the initial shotcrete lining is placed, to monitor tunnel deformation and build-up of load in the support. This provides information on tunnel stability and enables optimization of the load bearing rock mass ring.

Tunnel Measurement Systems

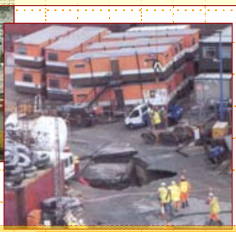


Legend	Measuring objective	Instrument
1	Deformation of the excavated tunnel surface	Convergence tape Surveying marks
2	Deformation of the ground surrounding the tunnel	Extensometer
3	Monitoring of ground support element 'anchor'	Total anchor force
4	Monitoring of ground support element 'shotcrete shell'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

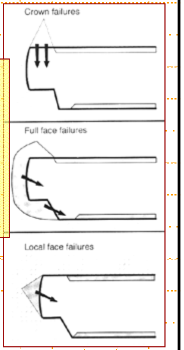
Key Elements of the NATM Philosophy

5) **Closing of Invert:** Closing of the invert to form a load-bearing ring of the rock mass is essential. In soft ground tunnelling, the invert must be closed quickly and no section of the excavated surface should be left unsupported even temporarily. For rock tunnels, the rock mass must be permitted to deform sufficiently before the support takes full effect.

The 1994 Heathrow tunnel collapse, a NATM tunnel in London Clays.



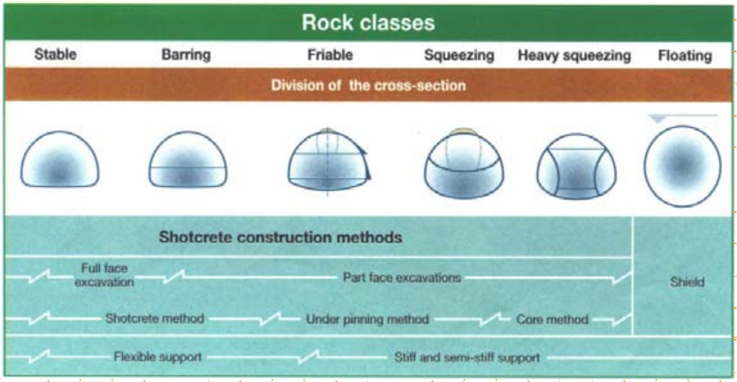
A review of NATM failures found that in most cases, the failure was a result of collapse at the face where the lining is still weak and cantilevered.



The builder and an Austrian engineering firm was fined a record £1.7m for the collapse, which put lives at risk and caused the cancellation of hundreds of flights.

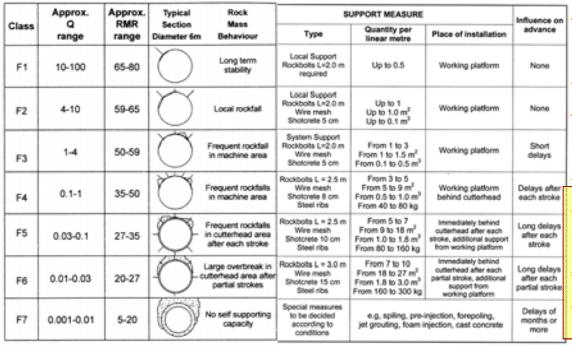
Key Elements of the NATM Philosophy

6) **Excavation Sequencing:** The length of the tunnel left unsupported at any time during construction should be as short as possible. Where possible, the tunnel should be driven full face in minimum time with minimum disturbance of the ground by blasting.



Key Elements of the NATM Philosophy

7) **Contractural Arrangements:** Since the NATM concept is based on monitoring measurements (i.e. observational approach), changes in support and construction methods should be possible and worked into the contractural system. All parties involved in the design and execution of the project - design and supervisory engineers and the contractor's engineers and foremen - must understand and accept the NATM approach and adopt a co-operative attitude to decision making and the resolution of problems.



Class	Approx. Q range	Approx. RMR range	Typical Section Diameter 6m	Rock Mass Behaviour	SUPPORT MEASURE			Influence on advance
					Type	Quantity per linear metre	Place of installation	
F1	10-100	65-80		Long term stability	Local Support Rockbolts L=2.0 m required	Up to 0.5	Working platform	None
F2	4-10	59-65		Local rockfall	Local Support Rockbolts L=2.0 m Wire mesh Shotcrete 5 cm	Up to 1 Up to 1.0 m² Up to 0.1 m³	Working platform	None
F3	1-4	50-59		Frequent rockfall in machine area	System Support Rockbolts L=2.0 m Wire mesh Shotcrete 5 cm	From 1 to 3 From 1 to 1.5 m² From 0.1 to 0.5 m³	Working platform	Short delays
F4	0.1-1	35-50		Frequent rockfalls in machine area	Rockbolts L = 2.5 m Wire mesh Shotcrete 8 cm Steel ribs	From 3 to 5 From 5 to 9 m² From 0.5 to 1.0 m³ From 40 to 80 kg	Working platform behind cutterhead	Delays after each stroke
F5	0.03-0.1	27-35		Frequent rockfalls in cutterhead area after each stroke	Rockbolts L = 2.5 m Wire mesh Shotcrete 10 cm Steel ribs	From 5 to 7 From 9 to 18 m² From 1.0 to 1.8 m³ From 80 to 160 kg	Immediately behind cutterhead after each stroke, additional support from working platform	Long delays after each stroke
F6	0.01-0.03	20-27		Large overbreak in cutterhead area after partial strokes	Rockbolts L = 3.0 m Wire mesh Shotcrete 15 cm Steel ribs	From 7 to 10 From 18 to 27 m² From 1.8 to 3.0 m³ From 160 to 300 kg	Immediately behind cutterhead after each partial stroke, additional support from working platform	Long delays after each partial stroke
F7	0.001-0.01	5-20		No self supporting capacity	Special measures to be decided according to conditions	e.g. spiling, pre-injection, forepoling, jet grouting, foam injection, cast concrete		Delays of months or more

Payment for support is often based on a rock mass classification completed after each drill and blast round.

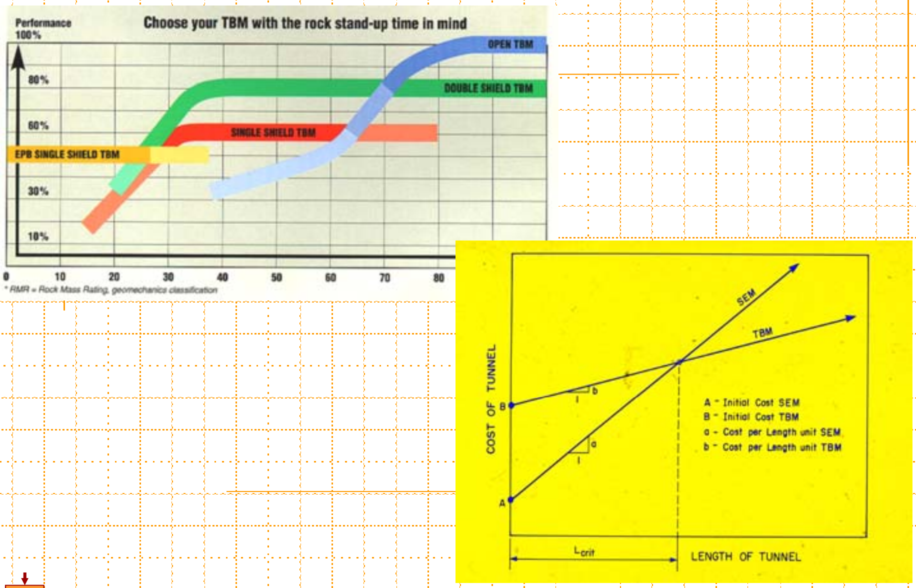
NATM: Advantages/Limitations

Advantages: The primary advantage of NATM is the economy resulting from matching the amount of support installed to the ground conditions, as opposed to installing support for the expected worst case scenario throughout the entire tunnel. The safety of the work is more easily assured because the sizes and configurations of the headings making up the total tunnel cross section can be adapted to the degree of instability of the working face.

Disadvantages: One of the chief problems is the need for cooperation between the Owner's and Contractor's engineers in deciding the amount of support to be installed from day to day. It is not easy to achieve this in the adversarial conditions often encountered. Also, the 'one man, one job' philosophy of union contracting tends to spoil the economic advantages since most of the tasks are necessarily performed sequentially, some of them by other trades. Daily production rates are often lower, and in soft ground, more support is generally required to support the working face, than with shield driven tunnels.

McCusker (1991)

Method Selection



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