Further Insights into the NATM

23rd Sir Julius Wernher Memorial Lecture.
When an invention is something new: from practice to theory in tunnelling

Dr. G. Sauer

Necessity is said to be the mother of invention, but plain curiosity or imitation of nature also leads to new developments. And like a tree, an idea or concept grows from an unknown number of roots or sources. Furthermore, its success depends essentially on where and when the seed is sown!

In tunnelling, the concept of using all available means, including the strength of the rock itself, to provide the maximum supporting capacity is obviously common sense. However, it was only through a long history of sometimes unrelated developments by often unrecognised and maligned pioneers that essential support technology was made available, and it was the renaissance of tunnelling in the late '50s and '60s that provided the necessary climate for the growth of a new philosophy and its related techniques.

In 1848, the mines head office of Pribram (south of Prague, now in Czech Republic) attempted by the use of fast-setting mortar to avoid heavy timber support in a coal mine at Wejwanow. At the same time, Karl Ritter, a Swiss engineer, proposed curved tunnel sections with immediate closure of the invert to provide a closed ring in any squeezing ground, probably as a result of the 1818 patent of Brunel's circular soft ground tunnelling shield.

Brains versus brawn

Rziha, the renowned nineteenth century German tunnelling engineer who proposed steel support instead of heavy and voluminous timber, acknowledged Brunel's Thames Tunnel as the most skilful soft ground tunnel and himself made remarkable contributions and inventions. His engineering philosophy in tunnelling was that it is much more skilful *to prevent* rock load than to handle it and the system necessary to handle the difficulties and heavy rock pressure in many cases derives from its source.

Shoterete was effectively invented in 1907 by Carl E Akeley, a taxidermist in Chicago, when he built a machine to spray mortar on the skeletons of dinosaurs to protect them against pollution. The large Arlberg, Simplon and St Gotthard Alpine railway tunnels were already in operation by then.

The first patent of the improved revolver shoterete machine was registered in Allentown, Pennsylvania, in 1911. At that time shotcrete was used mainly to protect slopes. In 1914 shotcrete was proposed for the first time for use underground to protect mine drifts against the atmosphere and to make them fireproof. The first recorded application of shotcrete in

tunnelling was in the USA in the early 1920s.

The New Austrian Tunnelling Method is often linked to a patent by Professor Ladislaus von Rabcewicz, who invented the dual-lining support for tunnels (initial and final support). This concept, however, had little to do with the application of shotcrete. It merely expresses the concept of letting the rock deform before the final lining is applied so that the loads are reduced. The idea behind the necessity for deformation was based on a theoretical investigation by Engesser in 1881 and was applied by Schmid in 1926.

The main achievement and contribution of Rabcewicz, Leopold Müller and the Austrians was the introduction of systematic anchoring and in-situ measurements based on the rock mechanics theory by the 'Salzburg Kreis'.

The original advocate of the use of shotcrete as immediate support in squeezing ground instead of the more traditional heavy timber or steel support was Anton Brunner, a little known mining engineer from Salzburg, Austria.

In 1954 Brunner assumed full responsibility for stabilising squeezing ground in a diversion tunnel for the Runserau power plant with the use of shotcrete, having been required to do so, in writing, for all claims against his own company and the consulting engineers. This was the first major incursion into the domain of the soft ground shield tunnellers. After this successful application he applied for a patent through his company, Rella, which showed no interest in the matter, leaving paperwork to the foreman, Anton Brunner. After he had obtained a patent and his method had been employed successfully in some other tunnels in Austria and Italy his company's interest in the method grew stronger.

What's in a name?

The 'Shotcrete Method', as the New Austrian Tunnelling Method was called at that time, gained worldwide recognition when it was applied under the consulting guidance of Professor L Müller and Professor L. von Rabcewicz in the Schwaikheim Tunnel in 1964. As both academics and practitioners they began to explain the method on a more theoretical basis in terms of the newly developed concepts of rock mechanics. The term 'New Austrian Tunnelling Method' (NATM) was created during a lecture by Professor Rabcewicz at the Thirteenth Geomechanics Colloquium in 1962 in Salzburg. International recognition of NATM sprang from Rabcewicz' articles in *Water Power* in 1964, but the name of the technique is still a controversial subject among experts worldwide.

The first successful application of the method in soft ground conditions in urban areas was in Frankfurt/Main in Germany in 1968. Brunner had for several years proposed the use of the NATM in urban areas but had so far been unsuccessful, his letters to leading figures in Austrian and German cities on the matter receiving a negative, if any, response. It was Professor Müller who interested the contractor Beton-und Monierbau to adopt the method and build a test tunnel in the Frankfurt Clay in 1968 that demonstrated its applicability.

This basic philosophy of retaining the initial strength of the surrounding ground by preventing substantial ground movement is the basic axiom of the NATM which is nothing new! It is therefore defined as a method of producing underground space by using all available means to develop the maximum selfsupporting capacity of the rock or soil itself to provide the stability of the underground opening. This is achieved by the application of smooth and appropriate resistant initial support and final lining (Fig 1). It should accept the necessary deformation but guard against the development of rock load.
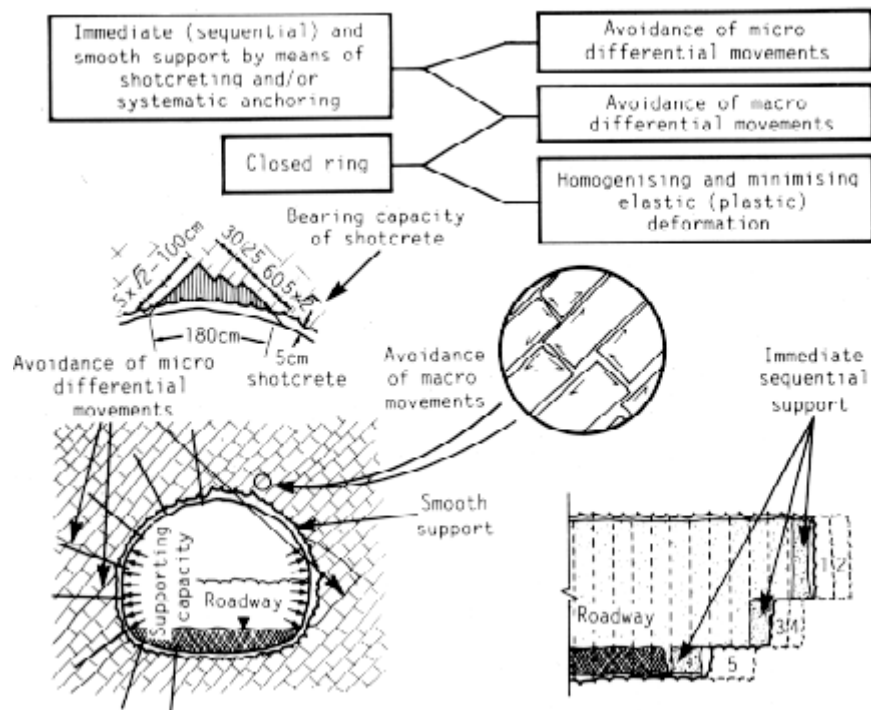

Fig. 1: Attempt at simplified definition of principles and effects of NATM.

The initial lining may consist of shotcrete, steel arches, rockbolts or whatever, singly or in combination. The NATM does not. however, merely comprise the use of shotcrete or anchors or the closing of the invert or the recently more popular use of a waterproof plastic liner to protect the inner lining against water ingress: tender treatment of nature is also involved.

One of the first publications on design methods for the shotcrete shell was that by Sattler (Fig 2), which was based on research that subsequently appeared in a thesis on the 'shear failure' theory of shotcrete by Gobiet.
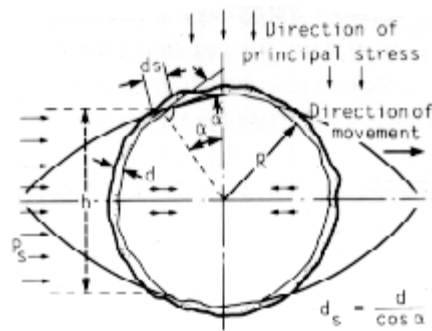
Fig. 2: Shear failure theory according to Rabcewicz and Sattler

After a few years of practical experience with this method in sensitive urban areas it was the question of which of two tunnels, one lying above the other, should be excavated first that started scientific investigation of the method (Fig 3).
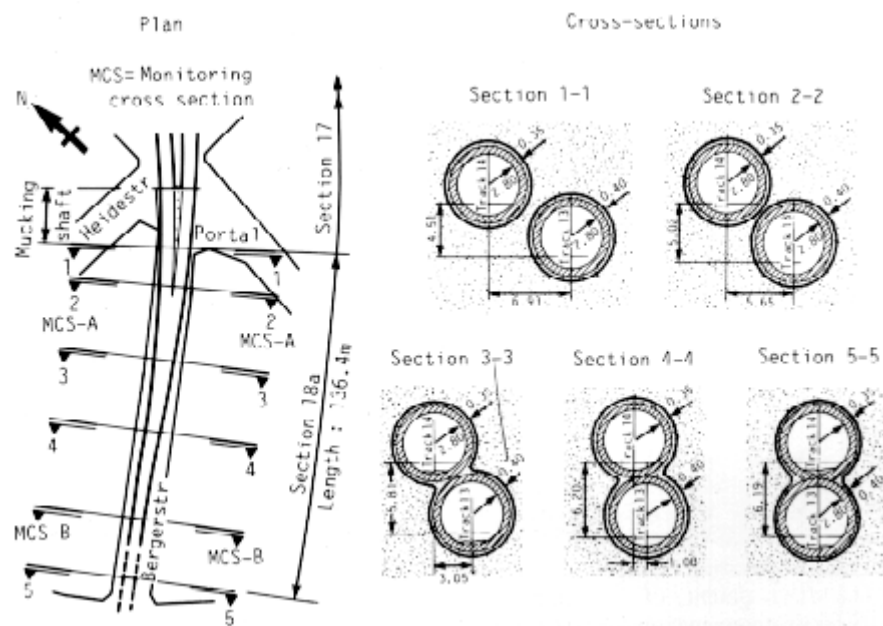

Fig. 3: Various sections along the line of the first NATM twin tube tunnel in an urban area.

Model tests and FEM calculations showed that there should be no replacement of the pillar area as in conventional methods where a pilot drift in the area of the middle wall is excavated first and backfilled with concrete, and that the lower tunnel should be excavated first and the upper tunnel second.

More fundamental questions arose on the subject of two parallel drifts in Frankfurt Clay with changing thicknesses of the earth pillar between them: Should the pillar be replaced by concrete via a preparatory drift? Should the drifts be excavated simultaneously and in parallel? If one drift is to be excavated ahead of the other, what should be the minimal distance between the headings.

Sophisticated model tests and computer analysis supported by a vast wealth of data obtained by previous scientific research into the field of soil and rock mechanics resulted in a number of new findings concerning the stress redistribution in the surrounding ground during and after a tunnel drivage. (This work is the subject of the author's doctorate thesis carried out at the Institute for Soil and Rock Mechanics, Technische Universität, Karlsruhe.)

The wave-like distribution of stresses around a cavity, abrupt displacement processes in sections of the surrounding rock mass and stress-reduced protective zones in areas close to the excavation are difficult to understand in terms of continuum mechanics but can be explained quite plausibly in terms of a time-dependent structural behaviour related to the material.

An initial consequence of the above findings for construction was the acceptance of the tunnel diameter as an essential parameter for the design of excavation procedures, establishing special provisions and specifications for the application of the initial support. It also serves now as a guideline for the prediction of excavation speed in difficult ground conditions in accordance with the setting time of the shotcrete.

By evaluating the results of a variety of model tests, as well as in-situ measurements it was possible to show that the first two periodic stress peaks accompany the drivage operations at linear intervals equal to approximately 1.5 times the tunnel diameter(Fig 4(a)). These stress concentrations (Fig 4(b)) lead to the periodic contractions, periodic deformations of bolting plates, cracks in the shotcrete, etc. if the support system is inadequate.
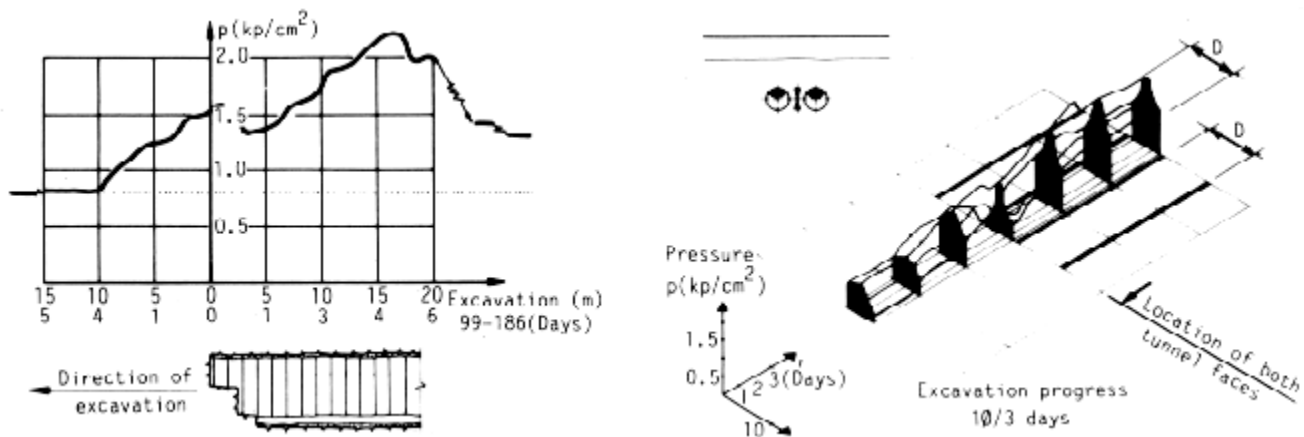

Fig. 4: (a) (left) Vertical stress evaluation in centre f middle wall between two subway tunnels dring simultaneous and parallel excavation of tunnels.
(b) (right) Three dimensional pattern of the measured vertical stress redistribution in the pillar.

Investigation of the results of a number of in-situ measurements suggests the occurrence of the following characteristic stress redistribution pattern in the vicinity of the tunnel.

Pressure increases relatively rapidly at about 1-1.5 diameter (Ø) in front of the face, remaining there until finally rising to an initial maximum approximately 0.5Ø in front of the face. A subsequent absolute stress minimum arises approximately 0.5Ø behind the face in the first third between the two maxima that contains and protects the excavation area. A second maximum occurs at about l.5-2Ø behind the face, provided that there is adequate support and the invert is closed. Relaxation of the second maximum takes several months, depending on the rheological properties of the rock. The reason for this is simpler than may be appreciated.

As a result of geometrical redistribution in front of the face, redistribution occurs in the rear section in line with the state of equilibrium (on average, 2Ø), so an increased concentration of stress must occur there automatically. This three-dimensional stress redistribution around the excavation area must peak (stress concentration) 1.5Ø behind the face to comply with simple geometrical laws (Fig 5).

Longitudinal section   Plan   Cross-section
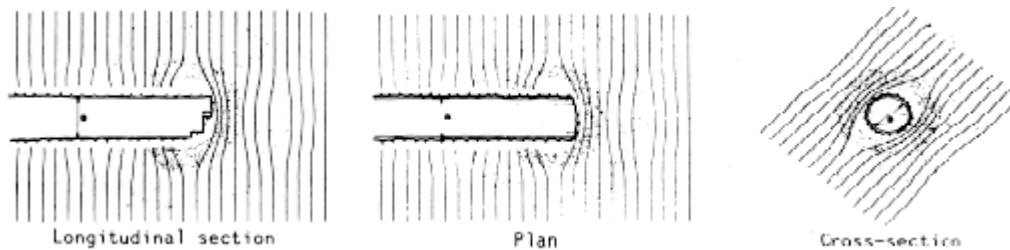
Fig. 5: Three-dimensional stress flow around excavation face
causing stress peak 1.5 diameter behind excavation face.

Comparing the difference between initial and residual friction or, rather, the post-failure behaviour of natural masses, the ground bearing capacity can certainly be sustained by avoiding convergence movements.

Therefore, in single-tunnel drivage in unstable rock conditions, the ring must be adequately supported within 1.5Ø of the face. Extension of the support ahead of the face by forepoling with rebar, grouted crown bars or metal plates may be necessary to counteract local ground instability.

If the ground has poor cohesion, the material inside the three-dimensional stress field has to be supported. This can be achieved either by forepoling, or by leaving a wedge of unexcavated earth to prop the face or in extreme cases, both.

In squeezing ground the rate of excavation has to be adjusted to the setting rate of the shotcrete. The invert shotcrete, the final phase of closing the ring, must have the minimum strength to sustain the peak stress 1.5Ø from the face. Even in more stable rock cut by a full-face TBM immediate support, if necessary, should be applied within this area.

One of the conclusions drawn in the author's thesis on observed stress redistribution patterns is that it is totally unnecessary to replace the dividing section of ground between two parallel

metro tunnels with a concrete filled drift and that it is in fact more beneficial to keep the headings structurally independent.

In twin tunnels where the central wall thickness is less than 0.7Ø the face of one tube must be at least of three-diameter length plus the thickness of the wall ahead of the second face. The practice of replacing the central wall with a concrete-filled pilot heading prior to tube excavation is therefore totally unnecessary.

The success of this concept - termed the 'Observational Method' by Peck - relies on the observation and measurement (Fig 6) of the interaction between the support and the surrounding ground.
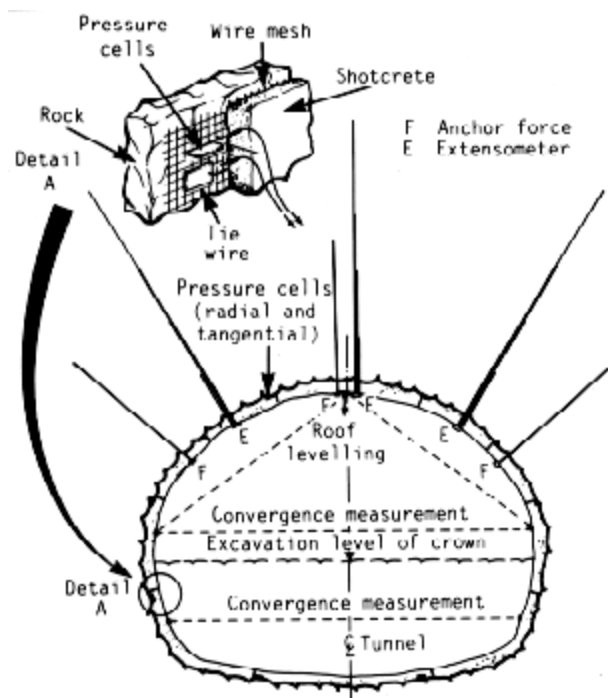

Fig. 6: Typical fully equipped monitoring cross-section

Convergence, roof settlement and other deformation measurements are common practice and valuable, but they give little indication of the actual stress in the shotcrete shell, which is more important to the assessment of the potential for failure. Flat hydraulic pressure cells, first introduced in 1958, are still the only available instruments for measurement of such stress.

Measuring stations should not be predetermined but placed where geomechanical changes or alterations in the cross-section dictate and the closer the measuring station to the face, the more frequent should be the readings. More frequent readings are often more valuable than increased instrumental accuracy. Indeed, cheaper, more frequent and less accurate readings from carefully chosen locations are more useful than infrequent but precise and expensive surveys. The value of any instrumentation is, however, only as good as its interpretation, which depends much more on the skill of an experienced engineer than on sophisticated computer software.

Moreover, the behaviour of the structure is influenced by unpredictable water conditions, unforeseen geological, geotechnical and tectonic anomalies and, above all, the human factor! Even rock classification systems cannot sufficiently solve this problem. The need for a flexible concept to meet the ever changing range of influences in tunnelling should therefore, be obvious.

If the special provisions for applying the initial support are determined too rigidly by means of calculations and excavations or construction plans, the natural feeling of responsibility of the miners at the face is reduced. This responsibility, the direct reaction of the miners and their supervisor to the given rock conditions, which includes their interest in their own safety, is an essential component and as important for the NATM as for any other free-face mining method. Planners, consultants and construction supervisors should always be aware of this and try to take advantage of the experience of the drivage crews.

The NATM concept has been applied to soft ground, especially in urban areas, because of its application advantages, free excavation area, considerable flexibility in regard to unforeseen changes in geological and hydrological conditions, flexibility in terms of cross-sectional changes, low transport cost for the contractor and a waterproofing system that provides a completely dry tunnel, under high water pressures and its competitive and economic price.
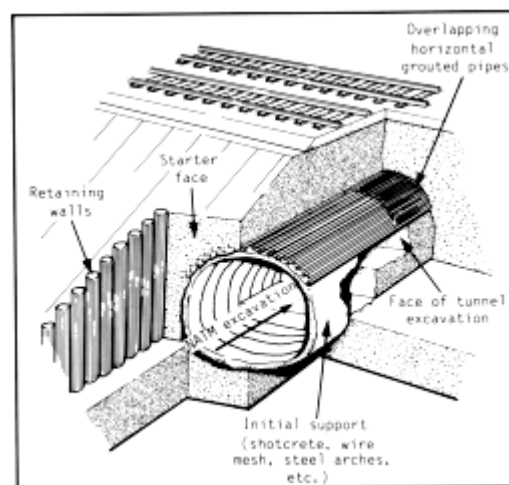

Fig. 7: Barrel vault method under a railway embankment.

Techniques for improving the soil, such as forepoling, grouted pipe spiling, grouting in section, freezing and compressed air, together with new techniques such as the so-called barrel vault method for crossing under railway or highway embankments (Fig 7), and the so-called door frame slab method for shallow NATM tunnels in soft ground (a semi-cut and-cover method, Fig 8), all provide consultants with a wide and flexible range of methods for use in different and changing conditions. There is, however, no real competition between the NATM and other techniques such as shield driving, for example; the most appropiate construction method in terms of safety and price should always be chosen. This flexibility should be provided by the bid documents.
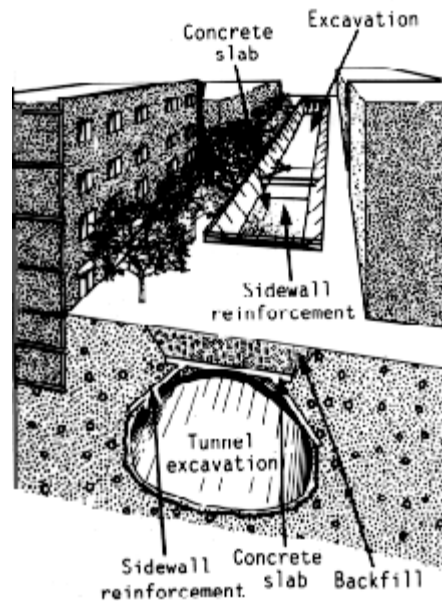
Fig. 8: Door frame slab method designed to minmise surface disturbance.

Although a shield or a TBM is usually much faster in uniform rock for long tunnels, the NATM does offer advantages and does reduce costs compared with traditional methods.

When pricing a contract the rock is classified and excavation and support are paid for according to the ground classification proposed by the contractor during the excavation and certified by the client (Fig 9). The primafy interest of the contractor is a good rate of advance; that of the client is to obtain a safe and economic structure. Agreement on rock classification is therefore usually easy to negotiate. The excavation volume is priced by class and immediate support by its volume/linear metre.
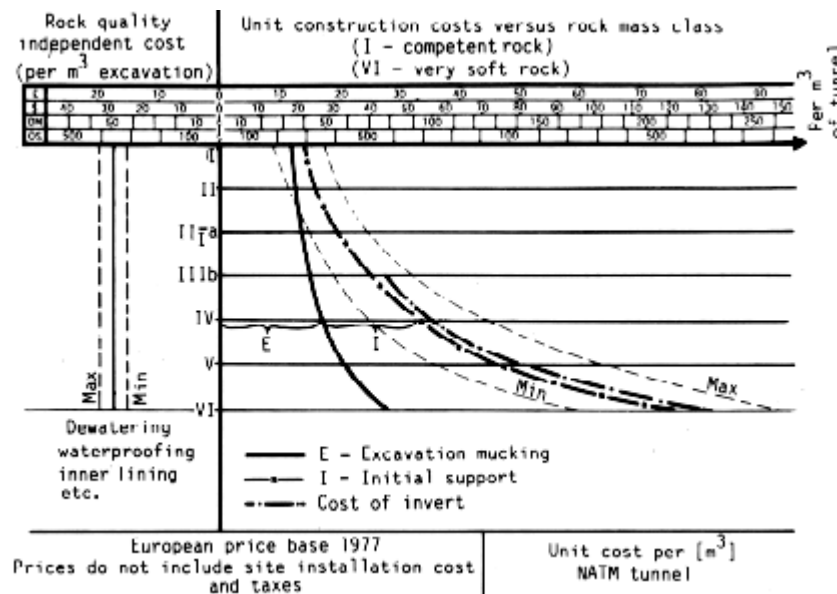

Fig. 9: Unit cost of excavation, initial support and invert

related to different rock classes.

The sooner appropriate support is applied, the smaller is the amount that is required and, hence, the lower is the cost.

In hard rock, including rock as weak as phyllite, the rate of advance can be as high as 15-25 m/day with three-shift (24-h) operation, whereas in soft ground, in such urban areas as Frankfurt, Munich and Vienna, an average of 4-5 m/day will be difficult to exceed.

Cost advantages

Price is also significantly influenced by the mucking arrangements particularly in urban areas. But in recent decades the unit price or price/linear metre has shown constant decline (Fig 10). Technological improvements are partly responsible, as is the increasing total volume of work, which has led to greater competition in the construction industry.
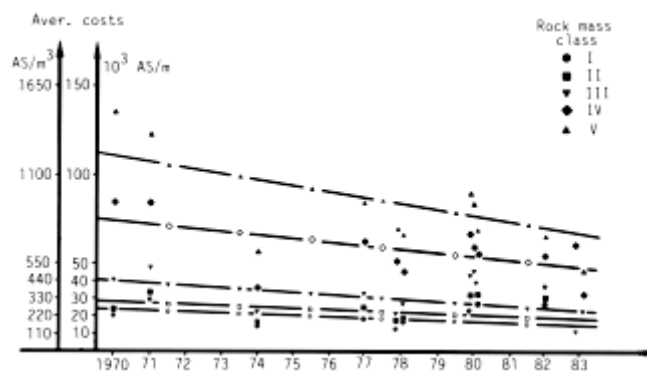

Fig. 10: Cost trend (1970-1983) of finished tunnel (including final lining) for two-lane tunnel with excavation section of approximately 80 m². AS=Austrian Schilling.

The NATM tunnels that were constructed recently by the Deutsche Bundesbahn for the high speed railway lines in West Germany in Bunter Sandstone, a medium-to-soft and in some cases extremely soft ground, produced a highly competitive cubic metre price for the finished tunnel. Depending on the rock class, the cost varies between 250 and 300 DM/m^3, which represents some 25 000-30 000 DM/linear metre of finished tunnel with a cross-sectional area of 100m^2. The cost of excavation and support, including inner lining, of a subway tunnel in urban areas in soft ground today is approximately 400-500 DM/m^3, or about 15 000-20 000 DM/linear metre for a cross-section of approximately 35-40m^2.

From 68 tunnel contracts constructed by NATM between 1980 and 1986 for the Deutsche Bundesbahn at a total estimated price of 3300 million DM, only a 15% overrun on the bid price has been recorded to date; this may be compared with nine contracts that used the cut-and-cover method on which total final costs of 500 million DM exceeded the tender amount

by 19%. Although the first NATM tunnel exceeded the tender sum by more than 50%, tunnels that were completed more recently have shown a final price that is much closer to that tendered.

Consistent application of the combination of praxis, observation and theory has led to enormous progress in civil engineering. The NATM is now widely used in one form or another all over the world.

One of the greatest enemies of progress, improved quality and innovation in industry, which includes tunnelling, is summed up by the two words. *Why me?*

Too few people are willing to accept responsibility. While remarkable advances have been made in science and technology, particularly in this century, man's nature has not evolved to keep pace.

It is to be hoped that future improvements in technology go hand in hand closer with those of humanity and fairness.

Bibliography

Barton N, Bandis S and Bakhtar K. Strength, deformation and conductivity coupling rock joints. *Int. J. Rock Mech Mech, Min. Sci.*, **22**, 1985, 121-40.

Barton N, Lien R and Lunde J. Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, **6**, 1974, 189-236.

Bawa KS. Development of shotcrete for metro construction in Washington. In *Use of shotcrete for underground structural support: proceedings of the Engineering Foundation conference, Berwick Academy, South Berwick, Maine. July 16-20 1973* (Detroit, Mich.: American Concrete Institute, 1973), 33-49. (*Spec. Publ.* no.45)

Brown E T. Putting the NATM into perspective. *Tunnels Tunnell.*. **13**, Nov. 1981, 13-17.

Brown E T. From theory to practice in rock engineering: 19th SirJulius Wernher Memorial lecture. In *Tunnelling '85* Jones M J ed. (London: IMM, 1985), ix-xxv; *Trans. Instn. Min. Metall. (Sect A: Min. industry)* **94**, 1985, A67-83.

Brunner A. Verfahren zum Bau von Stollen, Tunneln und Schächten in druckhaftem Gebirge. Austrian Patent 197851, July 15 1956; filed May 27 1958.

Brunner A. Die Spritzbetonbauweise beim Bau von Untergrundbahnen. *Öst. Ing.-Z.*, **9**, no.1 1966.

Heuer R E. Selection/design of shotcrete for temporary support. Reference 4, 160-74. 7.

Hoek E. Geotechnical considerations in tunnel design and contract preparation: 17th Sir Julius Wernher Memorial lecture. *Trans. Instn. Min. Metall. (Sect. A: Min. industry)*, **91**, 1982, A101-9.

Martin D. How the Austrians cracked the hard American nut with NATM. *Tunnels Tunnelling*, **16**, Dec.1984, 23-6.

Muir Wood A M. Ground behaviour and support for mining and tunnelling: 14th Sir Julius Wernher Memorial lecture. In *Tunnelling '79* Jones M J ed. (London: IMM, 1979), xi-xxii; *Trans. Instn. Min.*

Metall. (Sect. A: Min. industry), **88**, 1979, A23-34.

Muir Wood, Sir Alan and Kirkland C. J. Tunnelling hazards and risk-sharing. In *Tunnelling '85* Jones M J ed. (London: IMM,1985), 295-300.

Müller L, Sauer G and Chambosse G. Berechnungen, Modellversuche und in-situ-Messungen bei einem bergmännischenVortrieb in tonigem Untergrund (U-Bahn Frankfurt/ Main). *Bauingenieur*, **52**, 1977, 1-8.

Pacher F. Kostenanalyse für den Tunnelquerschnitt im Hinblick auf mögliche Kosteneinsparung und im Hinblick auf die Auswirkungen einer Erweiterung oder Einengung der Regelfahrbahnbreite von 7.50 meter. *Straßenforschung, Bundesministerium Bauten Technik, Vienna*, no.273, 1985.

Peck R B. Deep excavation and tunnelling in soft ground. In *Proceedings 7th International conference on soil mechanics and foundation engineering, Mexico, 1969, State of the art volume* (Mexico City: Sociedad Mexicana de Mecánica de Suetos, 1969), 225-90.

Rabcewicz L.v. The New Austrian Tunnelling Method. *Water Power*, 1964, 453-7, 511-4, Jan. 1965, 19-24.

14. Rziha F. *Lehrbuch der gesamten Tunnelbaukunst, Band II* (Berlin, 1872).

Sattler K. Österreichische Tunnelbauweise- Statische Wirkungsweise und Bemessung. *Bauingenieur*, **40**, no.8 1965, 297-301.

Wallis S. Counting the costs of NATM downfalls. *Tunnels & Tunnelling*, **19**, Oct.1987, 16-20.