Erroneous concepts behind the New Austrian Tunnelling Method

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The New Austrian Tunnelling Method (NATM) represents in the words of one of its main authors, L Müller, a 'structure of thought'. It will be shown in the following paper that this structure rests not on an established theoretical foundation but rather on two fundamental misconceptions. The first concerns the definition of the NATM itself, according to whose concept the rock mass (ground) becomes part of the support structure. Upon closer examination this concept is revealed to be unfounded because the ground inevitably becomes part of the support structure in any tunnel independently of the selected method of construction.

The second fundamental error lies in the claim that the NATM theory can optimise the design of the tunnel lining following the so-called Fenner-Pacher ground reaction curve. Since both theoretical and empirical justification is lacking for the existence of the latter, the central claim concerning the optimisation of the lining design is groundless.

In the final part of the paper, the question of why such misconceptions were able to gain such credence in the engineering community is discussed and why the NATM theory was able to survive for so long without being refuted. The reason is that the NATM operates with ambiguous or undefined terms, making it difficult to prove through logical argument that it is incorrect.

Official definition

In 1980 the Austrian National Committee on 'Underground Construction' of the International Tunnelling Association (ITA) published an official definition of the New Austrian Tunnelling Method in ten languages, which runs as follows[1]:

'The New Austrian Tunnelling Method (NATM) is based on a concept whereby the ground (rock or soil) surrounding an underground opening becomes a load bearing structural component through activation of a ring-like body of supporting ground'. The latter is referred to in the following simply as the 'ground ring'.

This definition contains three principal statements:

- the ground becomes a load bearing structural component;
- to achieve this a particular concept is required;
- the concept consists of the activation of a ground ring.

In the following analysis, emphasis will be laid on the published material of the authors of the NATM, i.e. L Rabcewicz, L Müller and F Pacher (often referred to as the 'fathers' of the NATM). Reference will also be made to the work of the second generation of NATM exponents.

Load bearing component

The definition emphasises that property of the NATM which distinguishes it from all related concepts, i.e. from other tunnelling methods. Presumably, under this method alone the ground becomes a structural component. From this basic statement other well known formulations have been derived and frequently reported in NATM literature:

- the support capacity of the ground is brought into play;
- the ground supports itself;
- the main load bearing component is the surrounding ground;
- the ground is transformed from a loading to a supporting medium;
- the self-supporting capacity of the ground is exploited;
- one works with and not against the ground, etc...

The claim that the NATM alone allows the ground to act as a structurally supporting component is basically false. In reality, tunnelling without the structural action of the ground is inconceivable. Whether the engineer employs a technical measure to support the underground opening or not makes no difference to the inherent support action of the ground. By trusting instinctively the mechanical laws governing a rock mass, man has occupied caves since early times. The idea of the ground as a structural element is inherent in the concept of a tunnel.

Thus the NATM claims for itself what is a universal necessity, which is also effective for all other methods of tunnelling and which characterises tunnelling *per se.*

For a correct definition, the NATM would have to have a characteristic which makes it differ, definition wise, from other tunnelling methods. Instead of this, the NATM has a basic property which is common to all methods of tunnelling. The NATM departs from the category of construction methods, slips into the definition of tunnelling in general and feels itself justified in regarding all other methods of tunnelling as being inherent in it.

In NATM circles, in fact, the question of the criteria according to which various construction methods can be classified under the NATM is discussed in earnest[2]. It is believed now that the NATM is not merely a method but rather a universal collection of knowledge and skill[3]. The concept of tunnelling is thus replaced by the concept of the NATM. Thereby the NATM would represent at one and the same time both the most comprehensive and the most vacuous concept in tunnelling. According to the laws of logic, the content of an idea decreases in relation to its size. From this it follows that, where NATM is concerned, it is not the construction method that is flexible, but rather the definition of the NATM, which can be stretched in an arbitrary manner.

As far back as 1879, Ritter observed that, from a certain depth of tunnel, the influence of the overlying rock was insignificant or had no influence on the rock pressure[4]. The rock mass itself supports the weight of overburden. Three years later (in 1882) Engesser proposed that an 'arching action' is induced in a cohesionless ground mass by a sagging of the tunnel roof[5]. The connection between rock deformation and rock pressure exerted on tunnel linings was recognised and clearly formulated.

In 1912, Wiesmann described the support function of the rock mass as follows "If the equilibrium state within a rock mass is disturbed by excavating an underground opening then the material particles surrounding the opening have to resist that pressure as an excess pressure which before was supported by the excavated material, as is the case when we make a hole in a wall."[6]

He further remarks: "The tunnelling engineer does not have the task of supporting the opening for the excess rock pressure. That is done by the protective zone. He has to be concerned with the preservation of this zone." By protective zone, Wiesmann understands the rock surrounding the opening in which stress redistribution occurs, that is — in a two-dimensional consideration — the plate (plane strain condition) with a hole in it. The protective zone is not sharply bounded.

Fifty years later, in 1962, the year the NATM was born, Rabcewicz wrote: "I think that today in the construction of underground openings we have come to realise that the supporting material is actually the rock mass itself", and adds: "To preserve as far as possible and to develop the support properties of the rock mass is thus the most important task of modern tunnelling."[7]

Rabcewicz completely failed to see that this view was already well known and taught in the textbooks of the day. Therefore, he did not apply this observation generally to the whole of modern tunnelling, but restricted it to the term 'New Austrian Tunnelling Method' which he introduced the same year. As a result, the conceptual difficulties of the NATM were built into it and still remain up to the present day. By 1962, the NATM was already based on an incorrect premise.

The members of the Austrian National Committee on 'Underground Construction', including Müller and Pacher, did not notice when drafting the official definition of the NATM[1] how deeply the support function of the ground had been anchored in the consciousness of engineers since the beginning of the century.

Here is another apt formulation by Maillart from 1923[8]: "If we construct a tunnel lining so as to withstand the external rock pressure acting on it, the strength of the rock mass is increased, thus enabling it to support itself."

In a lecture held in 1956, i.e. six years before the NATM was proposed, Mohr stated that "the forces acting on a lining will be smaller if the rock mass is allowed to deform a little"[9] and he continues:

"The practical use of this knowledge requires that the rock mass should only be supported to the extent that it becomes able to support itself."

In that the NATM claims exclusively to consider the supporting action of the ground, it not only commits a logical error but also ignores the achievements of those to whom credit is due for recognising and clearly formulating this fundamental law of tunnelling.

Activation of a 'ground ring'

Now we turn to the concept whereby, according to the official definition of the NATM, the activation of a ring-like body of rock or soil must result; the term 'ground ring' is used. This requirement is particular to the NATM way of looking at things and is not to be found in other literature on tunnel construction.

What is a ground ring? There are a number of answers to this question in NATM literature and in the brochure of the Austrian National Committee.[1] All these, however, differ fundamentally one from another. Here we summarise briefly the various, contradictory, ideas which are used by the authors of the NATM:

- the ground ring is also called the protective zone (Fig 1)[10];
- in earlier tunnel constructions the ground rings apparently run farther from the opening than is the case today with the NATM (Fig 1);
- the ground rings are frequently represented as ellipses (Fig 1);
- according to Rabcewicz[11] such rings are in contact with the openings, whereas for Müller and Fecker[10] they are not (Figs 1 and 2);
- the ground rings allegedly have to be mobilised by means of admissible rock deformations, otherwise they do not develop. If the rock deformation is insufficient, these ground zones do not close to a ring[1];
- from the point of view of tunnel statics only the lining[1] and the ground ring (Fig 3) should count. The latter seems to be loaded one way or another. Before the NATM concept the ground ring apparently did not play a part;
- in the case of multiple adit excavation method (Fig 4), a series of ground rings is supposedly formed which, according to the understanding of the NATM, is detrimental to the rock mass.[12] Thus the NATM propagates full face excavation as one of its main principles. Plastic zones interrupt the ground rings;[13]
- there are also reports of intact and residual ground rings;[3] the latter, however, do not close. What the difference is between the intact and the residual rock rings, however, is not explained;
- in the vicinity of a cavern the protecting zone, apparently, resembles the roof of a hall, i.e. it has the form of an arch.[14] But it is not clear on what this arch rests. It is also not clear why the ground ring is missing in the region of the invert;
- in the profile of the crossover point of the Channel Tunnel[15] the shape of the ground ring is particularly strange (Fig 5). At the top it is extremely thick, tapers increasingly towards the sides and does not close at the bottom;
- in NATM literature, descriptions of several concentric ground rings are to be found which are supposed to transform the rock mass to 'an onion skin shell structure'.[16] Whether these rings develop simultaneously or successively is not explained.

Essentially, the NATM works selectively with four basically different hypotheses of a supporting ground ring. According to the NATM, the ring can signify:

1. The protective zone according to Wiesmann (natural structural action) extending far from the opening;
2. Areas in the rock mass with maximum circumferential stress (protective zones);
3. The plastic zone; and
4. The rock zone defined by systematic anchoring (grid of anchors).

In NATM literature, authors shift arbitrarily between these four rather divergent hypotheses and the reader may find that, even in the same article, the meaning of the ground ring can undergo changes. It is therefore understandable that neither the authors of the NATM nor those who support is could ever give information on how to determine the shape and thickness

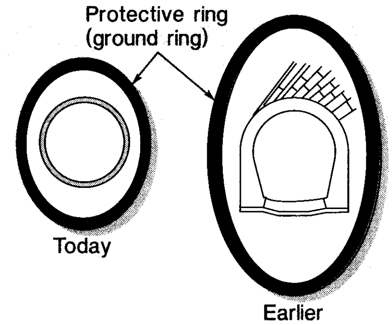

Fig 1. Ground ring (Müller[10]).

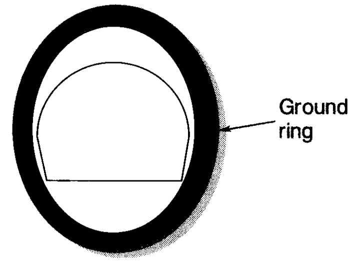

Fig 2. Ground ring according to Rabcewicz[11].

of such a ground ring. Even the material properties are not characterised. There are indications that the thickness of the ground ring is chosen arbitrarily[17]. Müller maintains that the closed ring shaped protective zones are for most tunnel engineers experienced reality.[13]

The NATM places conditions upon the establishment of the ground ring. One has to mobilise or activate it, else it does not form, or only gradually forms, or the ring closure is incomplete[1]. By the term 'activation' one author means systematic anchoring; the other, controlled rock deformations; and, yet another, waiting for a period of time to elapse, etc.

However, the ground ring may also be initiated by a shotcrete lining. One of the most widespread formulations asserts that the NATM 'permits' ground deformations and 'allows' time for the rock to support itself. Since, in tunnelling, rock deformations cannot be completely prevented by reasonable means and the installation of support measures inevitably takes time, this postulate is unacceptable and particularly misleading.

We summarise the results of our investigation of the official definition of the NATM as follows:

- The ground represents of necessity in the whole of tunnelling, independent of the selected tunnelling method, a structural component. The recognition of this phenomenon is emphatically not due to the authors of the NATM.
- The specific requirement of the NATM to activate the ground ring cannot be accomplished. The words 'ground ring' and 'activation' are so ambiguous that they are useless from a scientific standpoint. The definition of the NATM has proved to be murky, since it explains one unknown

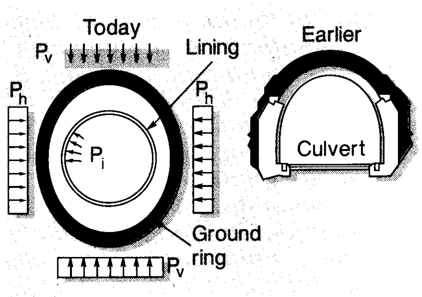

Fig 3. Ground ring (Müller and Fecker[10]).

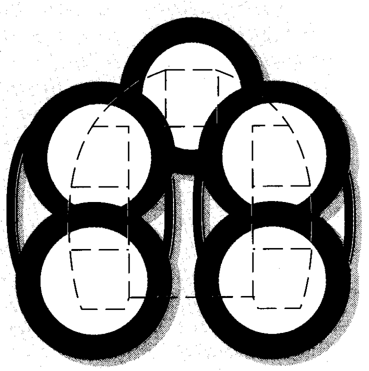

Fig 4. Ground rings around multiple adits (Müller[10]).

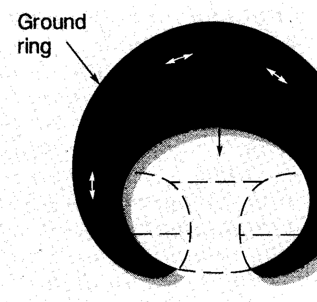

Fig 5. Specific form of the ground ring in the Channel Tunnel (Myers et al[15]).

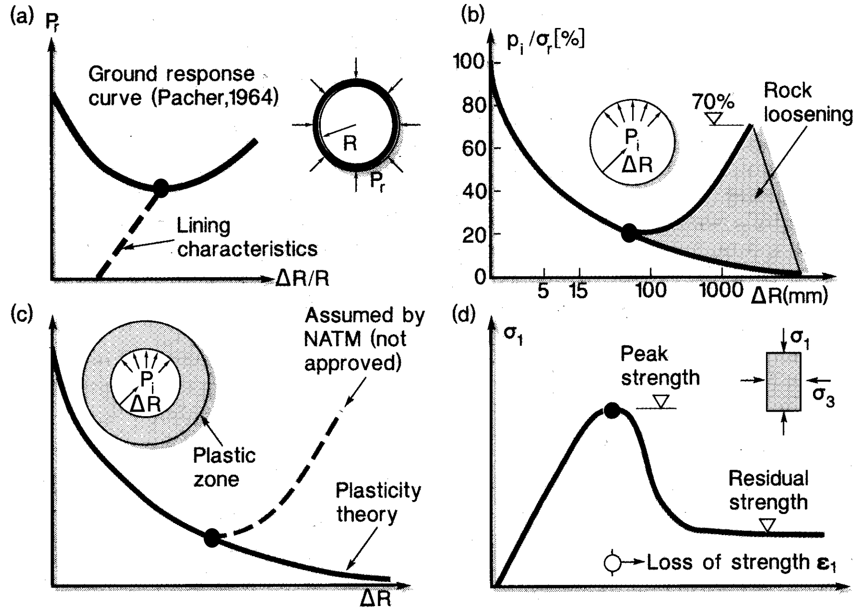

Fig 6. a) Optimisation of rock pressure[10]. b) Bifurcation of ground response curve due to strain softening in the rock mass[12]. c) Ground response curve according to plasticity theory in comparison with that of the NATM. d) Loss of strength in shear and triaxial tests.

(the NATM) with the aid of another unknown (structural activation of the ground ring).

Thus we have an explanation for the observation made by Müller and Fecker concerning the NATM, namely that "practically everyone who applies this method of construction has a different conception of it in his mind."[10]

Nothing has changed regarding the correctness of this statement since 1978. Thus, the question 'does the NATM really exist?' can be answered with an emphatic 'no'.

Minimising rock pressure

We now go a step farther and investigate the central idea of the NATM which concerns the minimising of rock pressure acting on the tunnel lining.

Since 1972, the hypothesis of Pacher[18] published in 1964, concerning the trough shaped ground response curve and minimalising the rock pressure and the lining thickness based upon it has become more and more central to the concept of the NATM[18]. According to Müller "the main concept of the NATM is based on Pacher's ground response curves."

What are we dealing with here? It is simply a matter of choosing the position and shape of the lining characteristics according to the NATM in such a way as to intersect the ground response curve of the rock at its lowest point (Fig 6a).[1, 10] Rabcewicz[19] is of the opinion that "with the aid of measurement one is in a position to keep the forces under control and the lining resistance, p_γ, can be chosen accordingly until an optimum value is achieved."

In Fig 6a) there is a representation following Müller and Fecker. The abscissa is the relative radial displacement ΔR/R and the ordinate the lining resistance p_γ. The axial symmetry of both the geometry and the stresses should be noted.

In Fig 6b a bifurcation of the curve may be observed.[12] The lower curve, which approaches the horizontal axis, is given by plasticity theory. NATM postulates a curve turning upwards, which is supposedly caused by rock loosening and straits softening. In this diagram, presented by Müller[12] the units of radial displacement are given in millimetres and the lining resistance as a percentage of the overburden pressure. Müller justifies the dramatic influence of loosening due to deformation as follows: "The higher the rock pressure, the greater the loosening of the rock; this increases in turn the rock pressure phenomena."[12]

Such a process is similar to a chain reaction (a reaction which, once induced, causes further reactions of the same type). If one considers Müller's diagram in Fig 6b more closely, the curve turning upwards seems to reflect the result of a chain reaction. One sees that the rise in rock pressure produced by rock loosening can reach about 70 per cent of the overburden pressure. For a tunnel situated at a depth of 1000m, the rock pressure, according to Fig 6b, would correspond to the weight of a column of rock of 700m. That this is impossible was clear even to engineers in the middle of the last century.

What is the reason for this extraordinary contradiction? It lies in the false assumption of a chain reaction in the rock mass. Indeed, there is no evidence theoretically or empirically for the existence of the ground response curve with a shape postulated by Pacher.

Only the ground response curve that results from the theory of plasticity is theoretically founded (Fig 6c). Whether or not a loss of strength (strain softening) is taken into account — as may be observed in a shear or triaxial test — the curve does not turn upwards. In a detailed research report[20] on the use of the ground response curves as a design basis for the NATM, the possibility of a trough-like Pacher curve is not even mentioned. In the ITA Guidelines there is also no mention of trough-like characteristic curves.[21] In the publications entitled 'Finite element analysis of the NATM'[22] and 'NATM and finite elements'[23], nothing is said about activated rock ring structures or a Pacher curve.

There is only one conceivable possibility of a deviation of the ground response curve from its downwards trend, which is also pointed out in NATM literature. This happens when, due to unfavourable jointing or the development of slip surfaces, a body of rock in a state of failure in the roof of the tunnel detaches itself partly or completely from the parent rock and, because of its self weight, increases the pressure on the roof lining. This possibility is also mentioned in the ITA Guidelines.[21]

At what point along the length of a tunnel, to what extent and at what time such sudden occurrences are to be expected cannot be predicted from calculations. It is important to note here that no chain reaction is thereby induced. The detaching of a body of rock about 5m high has only a small influence on the ground response curve in the roof region. This is confirmed by Rabcewicz when he states that "for the experienced tunnelling engineer, rock loosening is mostly harmless."[11]

Müller also says elsewhere that "in tunnelling we have in general to reckon with zones of rock loosening of 0.5 to 5m." NATM literature, however, warns of the damaging consequences of rock loosening. According to Rabcewicz, "the prevention of inadmissible rock loosening (is) an integral demand of the NATM."[24]

Rabcewicz creates the term 'admissible loosening'. This observation stands in contradiction to the above statement (loosening pressure is harmless). In addition, the concept of admissible loosening was never defined. Müller in 1978 correctly observed that "we have unfortunately no experimental evidence as to how much strain softening results from a certain amount of loosening."[12]

Regardless of what is understood by a ground ring there should be a relationship between it and the ground response curve. In the NATM literature, however, there is no relation whatever between the postulate of the activation of a ground ring and that of a ground response curve as proposed by Pacher.

To summarise: minimising the lining resistance in the sense of the NATM is not possible at all, because its prerequisite of a trough-shaped ground response curve according to Fig 7 cannot be explained theoretically and has never been verified empirically. Thus the principle of the NATM 'Construct the lining neither too early nor too late, and neither too rigid nor too flexible'[10] is without meaning. The optimum choice of the strength and deformation properties of the lining, as well as the time at which it is placed, must be based on other criteria. It represents one of the most difficult problems in tunnelling. Its treatment by the NATM amounts to an attempt to trivialise the problem, and thus tunnel design itself.

If a theory contains a gross error, it opens the door to even greater errors. The 'Theory and practice of the NATM' works, according to Sauer, with further types of characteristic curves.[25] "The observations, experiences and measurements made thus far require in summary an extension of the Fenner-Pacher curve to account for an additional maximum and minimum in the excavation zone."

The justification for this claim is an altered Pacher curve, which is supposed to show the relationship between six variables. Each coordinate axis represents not just one but three variables. To complete the total confusion, two of the six variables are not defined. The effort put into an unsound mathematical formalation might give the impression of its being scientific. It is incomprehensible that the ITA's Austrian National Committee for Underground Construction has not taken steps to stop such claims, although it acts in the manner of an institution against critics of the NATM.[26]

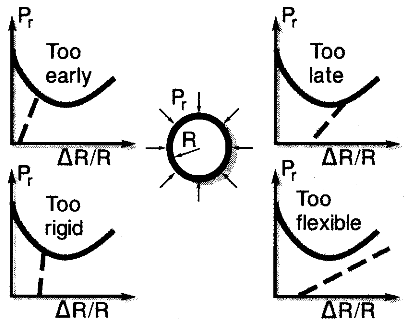

Fig 7. Sixth basic principle of NATM: 'Construct the lining not too early nor too late, and not too rigid nor too flexible'[10].

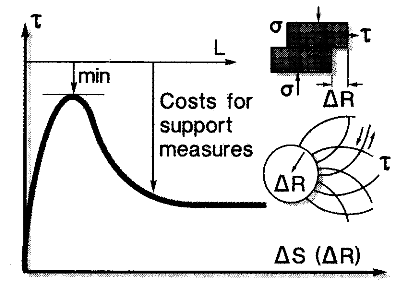

Fig 8. Unfounded relation between shear test, convergence, distance from the excavation face and costs for support measures (Sauer[25]).

General assessment

We close our evaluation of the NATM with a general assessment of its edifice of thought.[10] We all know that ideas and concepts form the backbone of our thinking and consequently of our judgements.[27] The basis of our scientific knowledge presupposes clearly defined concepts and sound ways of arriving at true conclusions. Knowledge without valid arguments or based on false premises cannot be true.

Table 1. Expressions from the literature*
Sensitivity to strain softening
Capacity for stress relief
Rate of stress relief
Semi stiff lining
Force vacuum
Bending moment filter
Pushing weight components
Pushing character of loading
Self protection effect
Structural reserves influenced by settlements
Stress shadows of the redistributions
Stress redistribution event
Stress event
Specific time factor
Necessity for stress redistribution
Admissible rock loosening

* As the meaning of these expressions is frequently not quite clear, even in the orginal German version, a literal translation is adopted in the English version.

If we consider the method by which the NATM develops its concepts, it may be seen that it works on the whole with 'nominal' definitions. By 'nominal definition' is simply meant 'words with no clearly defined meaning'. Nominal definitions, in contrast to 'real definitions', are only loosely related to concepts. The latter have a clear content. Thus only 'real definitions' are appropriate in a scientific field.

The examples taken from NATM literature and shown in Table 1 clearly show the pitfalls of merely creating words without clearly defined concepts.

How does language react to such a system of ideas? It begins to proliferate. A series of expressions related to the term 'ground ring' can be assembled from NATM literature (Table 2 in the January '94 issue of *Tunnel*). This variety of terms reminds us of Goethe's Faust:

'It's exactly where a thought is lacking
That, just in time, a word shows up instead.
With words you can argue beautifully,
With words you can make up a system.'
(Translation by Randall Jarrell)

If the definitions are imprecise, the judgements based on them must be either untrue or at least not binding. In NATM literature, incorrect or incomplete conclusions are to be found. An incorrect inference arises when the same word is used but with a different meaning, so that in fact several definitions are involved in the same conclusion.[27] Thus, the one who makes the judgement can always find a statement to fit the circumstances and allow inconsistent statements to stand side by side. A good example of a wrong conclusion is the description of how the ring-like rock support structure is activated.

An incomplete conclusion results if one or more premises in arriving at an evaluation are not stated. The claim of the NATM that the ground requires time for the development of a new state of equilibrium is an incomplete conclusion. Here one would have to add that this statement is only of practical significance in certain types of rock.

Confusion leading to bad judgement also occurs if a name is applied to ideas which is different from its common usage.[28] Such an arbitrary abuse of words is met in Sauer's representation of the ground response curve with additional Minima and Maxima.[25]

A bad error of judgement occurs, however, when knowledge is propagated without an attempt to justify it. An example of this is to be found in Sauer's 'Theory and practice of the NATM' in his diagram shown in Fig 8, which attempts to find a relationship between the following quantities:

- shear displacement (Δ S) and shear stress (τ) in a direct shear test;
- convergence of displacements (Δ R) and stance (L) of the ring closure from the excavation face.[25]

Sauer reports: "Analogously, the costs for rock support can be read off from this curve. They are given by the difference from an assumed need of minimum support measure at a maximum exploitation of the primary shear strength."[25]

Thus, in this diagram we should have, according to the NATM, a means at our disposal to determine the costs of support measures for a tunnel based upon a few laboratory shear tests. Depending on the shape of the shear strength diagram, the costs would rapidly rise at a certain distance to the excavation face.

This theory of the NATM after Sauer has not been validated. Furthermore, it cannot be validated. In fact, it can easily be shown that such relations simply cannot exist. Such misleading curves give the reader the impression, however, that under the NATM method one obtains information which cannot be gained from any other tunnelling method.

As a last example of mistaken judgement in NATM literature we consider the following statement which is basic to the NATM:[1]

"Adaptation of the methods of construction and operation to changing rock properties, to the stand-up time as well as to the stability of the excavation face by the right choice of area and depth of attack."

On careful perusal of the above it is evident that in this basic statement two expressions occur, along with their synonyms. In tunnelling, by method of construction and operation is understood the procedure followed in excavating the cross section, i.e. the choice of the area of attack, e.g. full or partial cross section, and under method of operation the depth of this attack. Thus this statement of the NATM contains a tautology, and merely says:

"Adaptation of the methods of construction and operation using the right choice of the methods of construction and operation." How the right choice should be made, which is the heart of the matter, is not answered.

Conclusions

It is impossible to conduct a critical discussion of the NATM within its own framework of ideas: its terms are so ambiguous that they defy close examination. If one considers the NATM as a whole in a wider context, not only is it not free from criticism, it is simply groundless. ■

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