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An insight into the New Austrian Tunnelling Method (NATM)

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ABSTRACT: The objective of this paper is to investigate a particular tunnelling method, known as the New Austrian Tunnelling Method (NATM), which first appeared in English publications in 1964. NATM was described as a modern tunnelling method by Rabcewicz. Throughout the literature survey, there have been encountered numerous ambiguities and conflicts relating to the NATM. Furthermore, researchers who devoted themselves to tunnelling technology are split into three groups. These are the supporters of the early precursors of the NATM as a new modern tunnelling method (Müller 1978; Golser 1979), the opponents as nothing new and Austrian, and the neutral group. The ultimate criticism against NATM, denying its existence, has been made by Kovári (1994). The applications of this method, however, have accelerated all over the world due to its overwhelming beneficial features compared with other conventional tunnelling methods. Sometimes, NATM is referred to using different titles such as Sprayed Concrete Lining (SCL) (ICE, 1996), Sequential Excavation Method (SEM) as distinct from NATM (Brandt et al. quoted by ICE 1996), CD-NATM, Centre Dividing wall NATM (Kobayashi et al. 1994), CDM, Centre Diaphragm Method (Seki et al. 1989) or CRD-NATM, Cross Diaphragm Method (Narasaki 1989) and UHVS, Upper half vertical subdivision method (Seki et al. 1989). Detailed definitions for NATM are available in the literature and the historical background with characteristic features will be discussed in paper.

1 INTRODUCTION

The first application of NATM in the mining industry in the U.K (Deacon & Hughes 1988) was followed by the Round Hill Road tunnels as the first NATM designed UK highway tunnels (Bowers 1997). The collapse of the Heathrow Express Rail Link Station tunnels on 21 October 1994 forced the method to be put under close examination. The Health and Safety Executive (HSE) carried out an investigation and published its findings in a book for NATM design for safety (1996). An investigation was also followed by the Institution of Civil Engineers (ICE) (1996). At the beginning of the new millennium, some conflicts still remain. Therefore, this paper is aimed to describe the causes of NATM collapses and review failure cases that have occurred in different geological conditions around the world.

2 HISTORICAL BACKGROUND of NATM

The chronological development of the NATM method has been summarised by many researchers in relation to the support systems used (Table 1). These historical advances leading to NATM will be described here once more to be able to see the developments and applications of NATM.

Several pioneers have made important contributions to tunnelling which have produced the NATM. Sir Marc Isambard Brunel in the early 19th century, introduced a circular shield for soft ground tunnelling (British patent no.4204). Following this, another important contribution was made by Rizha, a German tunnelling engineer. He introduced steel support instead of heavy timber. He also advised that the system that was necessary to handle the difficulties of heavy rock pressure in many cases was its source (Sauer 1988) implying the role of surrounding rock as a part of the support system which is believed to be the key principle of NATM by Rabcewicz (1964). During the 1910s, after the invention of the revolver shotcrete machine by a taxidermist Carl Akeley, shotcrete was used in mines in United States and spread to the Europe in the early 1920s. In 1948, Rabcewicz invented dual-lining supports (initial and final support) expressing the concept of allowing the rock to deform before the application of the final lining so that the loads on lining are reduced. Professor Kovári (1994), however, considers the idea behind this concept as Engesser's arching action published in 1882. The dual-lining concept is followed by the term New Austrian Tunnelling Method that was proposed during a lecture by Rabcewicz in 1962 and it gained international recognition two years later. The first application of NATM in soft ground was the Frankfurt metro in 1969.

Table 1 Chronological developments leading to NATM (reproduced from Sauer 1988 & 1990; Rabcewicz 1964)

Years	Developments
1811	Invention of circular shield by Brunel.
1848	First attempt to use fast-setting mortar by Wejwanow.
1872	Replacement of timber by steel support by Rziha.
1908-1911	Invention of revolver shotcrete machine by Akeley.
1914	First application of shotcrete in coal mines, Denver.
1948	Introduction of Dual-lining system by Rabcewicz.
1954	Use of shotcrete to stabilize squeezing ground in tunnelling by Bruner.
1955	Development of ground anchoring by Rabcewicz.
1960	Recognition of the importance of a systematic measuring system by Müller.
1962	Rabcewicz introduced the New Austrian Tunnelling Method in a lecture to the XIII Geomechanics Colloquium in Salzburg.
1964	English form of the term NATM first appeared in literature produced by Rabcewicz.
1969	First urban NATM Application in soft ground (Frankfurt am Main).
1980	Redefinition of NATM due to conflict existing in the literature by the Austrian National Committee on Underground Construction of the International Tunnelling Association (ITA).
1987	First NATM in Britain at Barrow upon Soar mine

3 CHARACTERISTICS FEATURES and PHILOSOPHY of NATM

What is NATM? What are the essential features of NATM? Is NATM a tunnelling technique or a philosophy? Similar questions arose after the international recognition of NATM that required to be answered to ensure the principles of this '*philosophy*' or '*technique*' are correctly understood in the tunnelling industry. These issues gained interest of many scientists, practitioners and technical journalists to determine the true concepts of NATM. Therefore, the issue will be reviewed again regarding the existing and new definitions.

When we go back to the origin of NATM, Prof. L.v. Rabcewicz (November 1964), the principal inventor, explains the method as:

"…A new method consisting of a thin sprayed concrete lining, closed at the earliest possible moment by an invert to a complete ring –called an "auxiliary arch"- the deformation of which is measured as a function of time until equilibrium is obtained"

He emphasized three key points, the first is the application of a thin-sprayed concrete lining, the second is closure of the ring as soon as possible and the third is systematic deformation measurement.

The definition given above has then been redefined by the Austrian National Committee on Underground Construction of the International Tunnelling Association (ITA) in 1980 to remove the conflicts that arose in the literature (Kovári 1994). This is as follows:

"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".

Another recent definition on NATM given by Sauer (1988) states that NATM is:

"…A method of producing underground space by using all available means to develop the maximum self-supporting capacity of the rock or soil itself to provide the stability of the underground opening."

Using the statement "all available means", he defines the method in a more general fashion than it was already defined by his fellow Austrian practitioners.

One of the other advocates of NATM, Prof. Dr. Leopold Müller (1978) proposed that

"The NATM is, rather, a tunnelling concept with a set of principles… Thus in the author's opinion it should not even be called a construction method, since this implies a method of a driving a tunnel".

As a result of the above statements, it is clearly agreed by the Austrian proponents that NATM is an approach to tunnelling or philosophy rather than a set of excavation and support techniques. Golser, (1979), Brown, (1990), Hagenhofer (1990), Barton (1994) are supporters of this idea amongst many other scientists.

Prof. Müller (1990), who was extremely keen to explain the key principles of NATM, summarised the important characteristic features of NATM amongst the other twenty-two principles as:

i. The surrounding rock mass is the main load bearing component and its carrying capacity must be maintained without disturbance of the rock mass.

ii. The support resistance of the rock mass should be preserved by using additional support elements

iii. The lining must be thin-walled and necessary additional strengthening should be provided by mesh reinforcement, tunnel ribs and anchors rather than thickening the lining.

iv. The ring closure time is of crucial importance and this should be done as soon as possible.

v. Preliminary laboratory tests and deformation measurements in the tunnel should be carried out to optimise the formation of the ground ring.

However, his conclusion about a rapid ring closure time in deep tunnels to minimise deformations was not agreed by Rabcewicz and Pacher according to their report in 1975 (Golser 1979), which states:

"However, the principle of ring closure as quickly as possible is only applicable to tunnels in rock with low primary stresses. In tunnels with large overburdens and poor rock quality only a stress to the largest extent possible will achieve the object. Of course, this stress relief, which will continue for many months, must be controlled most accurately by measurements."

In summary, the following major principles, which constitute the NATM, can be derived from the following references; Tunnels & Tunnelling (1990), Will (1989), Brown (1990), Wallis (1995), ICE (1996), HSE (1996), Bowers (1997), Fowell & Bowers, (1998) as follows:

i. The inherent strength of the soil or rock around the tunnel domain should be preserved and deliberately mobilised to the maximum extent possible

ii. The mobilisation can be achieved by controlled deformation of the ground. Excessive deformation which will result in loss of strength or high surface settlements must be avoided

iii. Initial and primary support systems consisting of systematic rock bolting or anchoring and thin semi-flexible sprayed concrete lining are used to achieve the particular purposes given in (ii). Permanent support works are usually carried out at a later stage.

iv. The closure of the ring should be adjusted with an appropriate timing that can vary dependent on the soil or rock conditions.

v. Laboratory tests and monitoring of the deformation of supports and ground should be carried out.

vi. Those who are involved in the execution, design and supervising of NATM construction must understand and accept the NATM approach and react co-operatively on resolving any problems

vii. The length of the unsupported span should be left as short as possible

These elements intend to embrace all definitions including many types of tunnelling requirements and ground conditions. However, Murphy, (1994) proposes that:

"…It can be argued that a particular application does not have to involve every element-nor indeed can it- in order to be legitimately classed as a NATM project."

3.1 The Rabcewicz shear failure theory around an opening

Recalling his failure theory when a cavity is made in rock, the stress rearrangement occurs in three stages as seen in Figure 1. At first, wedge-shaped bodies on either side of the tunnel are sheared off along the Mohr surfaces and move towards the cavity (I). In stage two, the increase in the span leads to convergence of the roof and floor. The deformation at the crown and the floor of the cavity increases more and the rock buckles into the cavity under the constant lateral pressure (III). The pressures that arise in stage (III) are termed "squeezing pressures" and rarely occur in civil engineering activities due to shallow depth of excavations. Then, Rabcewicz (1964) draws a conclusion that

"…Recognising progressive occurrence of pressure phenomena as described above, because, with the obsolete methods then used, the sections were usually not driven full face but divided into subsequently opened out…"

He validates the excavation method that should be sequential rather than full face by his shear theory.

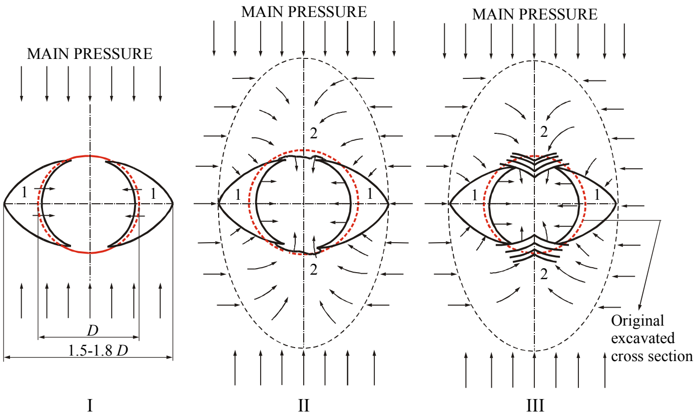

Figure 1 Mechanical process and sequence of failure around a cavity by stress rearrangement pressure (after Rabcewicz 1964)

3.2 Proposed NATM support systems by Rabcewicz

Support systems as proposed by Rabcewicz (1973) fall into two main groups.

"The first is a flexible outer arch-or protective support-design to stabilize the structure accordingly, and consists of a systematically anchored rock arch with surface protection mostly by shotcrete, possibly reinforced by additional ribs and closed by the invert…

The second means of support is an inner arch consisting of concrete and is generally not carried out before the outer arch reached equilibrium…"

To be able to design the load bearing capacity of the lining for different types of rock or soil, the phenomena of shear failure, explained earlier, should be interpreted accordingly. The relationship between the disturbed ground around the cavity, "protective zone" and the bearing capacity of the support, "skin resistance" is required to be established (Rabcewicz 1964). Mathematical representation of these relations is described by Kastner as:

$$p_i = -c\cot\phi + p_0\left[c\cot\phi + (1-\sin\phi)\right]\frac{r^{\frac{2\sin\phi}{1-\sin\phi}}}{R} \qquad (1)$$

Omitting the cohesion, the Eq. (3.1) yields to

$$p_i = p_0(1-\sin\phi)\frac{r^{\frac{2\sin\phi}{1-\sin\phi}}}{R} = np_0 \qquad (2)$$

The values of n are given as a function of p_0 and ϕ (see Rabcewicz 1964). Assuming no protective zone in which r=R, then the opening reaches equilibrium without any deformation. The formulae given above are derived according to the stress distribution after a cavity has been made, as is sketched in Figure 2.

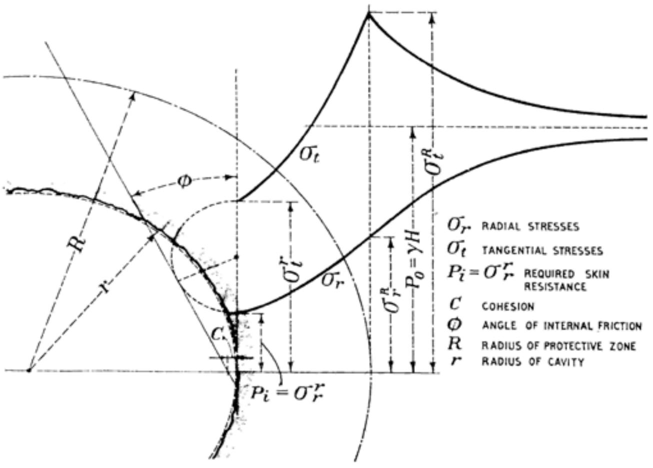

Figure 2 Stress distribution around a cavity under hydrostatic pressure (after Kastner, quoted by Rabcewicz 1964)

The ground response curve (Figure 3) shows the rock/support interaction and deformations in time. It provides a tool to idealise support stiffness and time of installation. When a stiffer support (shown as '2') is chosen, it will carry a larger load because the rock mass around the opening has not deformed enough to bring stresses into equilibrium. Thus, the safety factor will sharply decrease. After point C, ground behaviour becomes non-linear. If the support (1) is installed after a certain displacement has taken place (point A), then the system reaches equilibrium with a lower load on the support. Thus, Rabcewicz (1973) concluded, "It is a particular feature of NATM that the intersections always take place at the descending branch of the curve". This implies a less stiff support which causes the required deformation as in the case of a NATM application. Moreover, he stressed that rock support should be neither too stiff nor too flexible. After the point B "detrimental loosening" starts and the required support pressure to stop the loosening increases greatly. However, if the support is applied at the right time for the correct deformation, the support pressure takes the minimum value at this point.

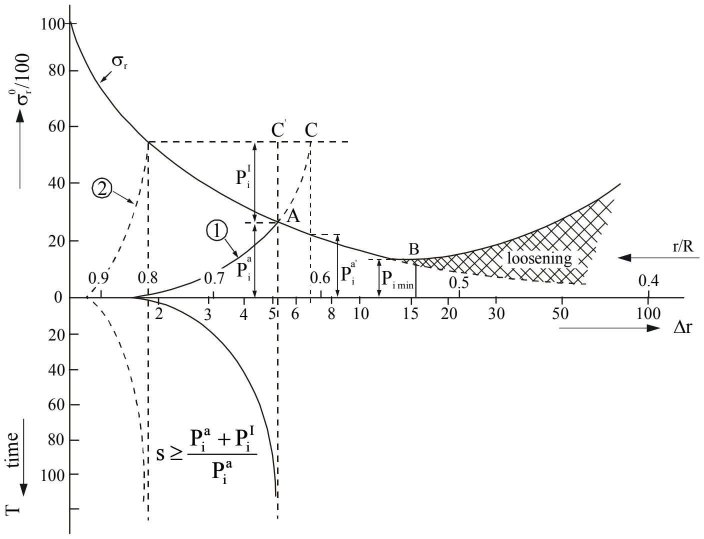

Figure 3 Ground-support interaction curves (after Fenner & Pacher, quoted by Rabcewicz 1973)

Rabcewicz also concluded the following points in regard to the reciprocal relationship of the basic supporting system of NATM, which are shotcrete and the anchored rock arch:

i. With the same type of rock and overburden relationship between the size of the joint bodies and the excavation area is decisive for the mobility of the material

ii. With small sections (i.e.10-16 m²) and joint bodies of a few dm³, a simple shotcrete sealing with d = 3 cm = 0.017×R usually stabilises the tunnel

iii. With an underground power station of 400-600 m² on the other hand, a rock with joints bodies of this size behaves like a cohesionless mass, and a simple shotcrete lining of 0.017×R = 19-24 cm would never do. A systematically anchored rock arch is imperative in this case.

3.3 Sprayed Concrete Lining (SCL) or NATM?

As has been discussed earlier, NATM has been redefined by some institutions and even by some authors by means of adding new features or disregarding some of its main principles to serve their particular tunnelling purposes or to clear the so-called conflicts that have arisen from that. They have remoulded or tailored as a distinctive tunnelling philosophy and/or technique to fit into these definitions. NATM has been renamed Sprayed Concrete Lining (SCL) by the Institution of Civil Engineers (1996) for soft ground applications. They claimed that any soft ground application of NATM is associated with the following principal measures:

a) Excavation stages must be sufficiently short, both in terms of dimensions and duration.

b) Completion of primary support-in particular, closure of the sprayed concrete ‘ring’ must not be delayed.

Since these two measures are not applicable for the original NATM philosophy for soft ground, any application of that in urban areas is the preliminary application of the sprayed Concrete Lining (SCL) (ICE 1996). Moreover, this claim is extended as;

“In practice, in soft ground in urban areas, that which is referred as NATM is preliminary sprayed concrete as primary support, followed at a predetermined later date by installation of a permanent lining. Details of the primary support (e.g. thickness of sprayed concrete) are determined by the designer and then not usually varied. Instrumentation is used to monitor performance and safety of the primary support and thereby validate its design…

…In summary, the use of sprayed concrete lining of tunnels in soft ground in urban areas does not employ any claimed NATM philosophy, but rather it is the use of construction techniques often associated with NATM…”

Another definition was introduced by Health and Safety Executive (HSE) (HSE 1996) following the Heathrow Express Tunnel (HEX) collapse. The report prepared by HSE is concerned with the safety measures taken during and after construction of a tunnel and how they can be designed safely disregarding what the term should be used for NATM. According to this definition, NATM (denoted bold italicised) is described as;

“A tunnel constructed using open face excavation techniques and with a lining constructed within the tunnel from sprayed concrete to provide ground support often with the additional use of ground anchors, bolts and dowels as appropriate.”

Bowers (1997) has provided an insight to the theory and application of NATM with two case studies (Bowers 1997; New & Bowers 1994) and he noted regarding the HSE definition that

“The issue of the definition was, however, seen as being of less relevance to safe working practices than the nature of procedures employed and so was not explored in great detail.”

In summary, whatever NATM is called or defined, it still carries the distinctive features amongst the other conventional tunnelling methods and its application continues under different names around the world. However, these definitions merging in a sense that

i. Utilisation of ground as a part of support is the main concern.

ii. Application of the primary lining to reach equilibrium at the optimum deformation with possible additional support elements, such as rock bolts, steel arches, ribs etc.

iii. Closing the ring at an appropriate time by using the ground support interaction curve and monitoring the ground response with systematic measuring systems

iv. Stabilisation of the tunnel by use of a secondary lining

v. Dimensioning the excavation portions of the tunnel dependent on the ground conditions.

3.4 Design criteria and features of NATM

The principles for an appropriate design methodology for NATM can be divided in two main design groups. The first could be considered as a function of NATM technical requirements with the application in soft ground or rock regarding support system. The second is dependency on the external constraints, such as settlement problems, environmental impacts, safety, engineering technology, and contractual and financial constraints. Golser & Mussger (1978) note, for example, the importance of the contractual design for the NATM that plays a greater role for the successful economic application of NATM. In addition, the contract requirements of a client may effect the satisfactory completion of the works at minimum costs, which can result in changes to the entire design procedure.

The Institution of Civil Engineers (1996) categorised tunnel design philosophies into three broad groups as illustrated in Figure 4. This general classification is also interrelated to each tunnelling philosophy according to the supports used. Thereby, NATM is interpreted as the combination of the traditional hard and soft ground tunnelling philosophies.

As a general design philosophy for NATM, the essential aspects for design are illustrated in Figure 5. Because, each of these aspects is part of the entire design process, individual design of these features unless integrated with each other may cause failure of the NATM. After determination of the geometry and size in respect to its application in soft ground and/or rock mass, NATM design is mainly related to its support characteristics.

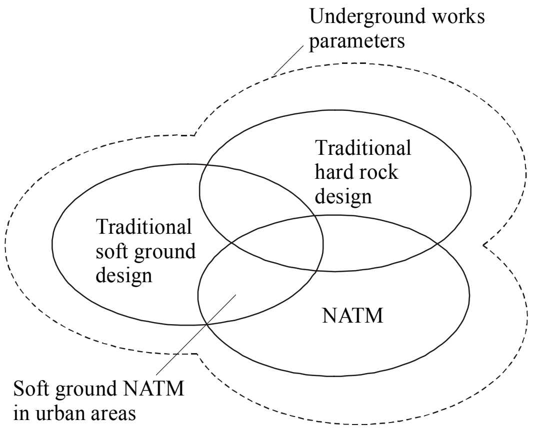

Figure 4 Interrelationships of tunnel design philosophies (after ICE 1996)

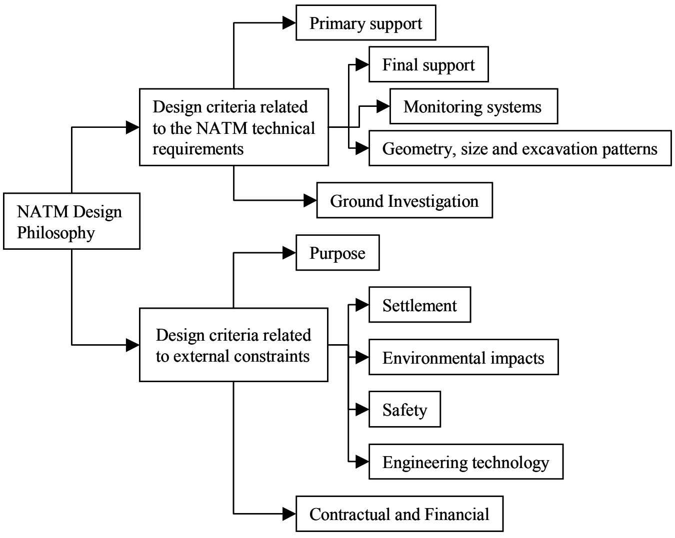

Figure 5 General design aspects for NATM

3.4.1 Primary and final support design

Support design for both shotcrete and the final lining is the main component of the NATM technical design. The flexibility and the thickness of the primary support with the additional of steel weld mesh or steel fibre reinforcement and rock bolts, forepoling and spiling especially for face stability has to be taken into account in the support design. The time dependency of the lining should be specifically subjected to design considerations as well. The timing for the closure of the ring can be optimised accordingly.

For the initial support design, Rabcewicz (1965) suggests that

"A design of shotcrete should attain a high carrying capacity as quickly as possible, and it must be rigid and unyielding so that it seals off the surface closely and almost hermetically."

He points out the important point that shotcrete must gain its maximum carrying capacity in a short time.

On the other hand, Vavrovsky (1995) provides an insight for the rock deformation and stress redistribution phenomena associated with NATM applications in rock and soil and he emphasis that

"…The scope of the design is consequently not to support itself but a package of measures including sealing, reinforcement and support of the rock mass during the redistribution process…"

Therefore, the design of the support system is required to be integrated to the deformation characteristics of the ground. Then, the load bearing capacity of the media and the support system can be best understood by the rock support interaction diagram (see Figure 3). From these curves, the amount of support required to stabilise the tunnel can be obtained. Providing an adequate support at optimum time will result in a small amount of support leading to lower cost. If the support elements are installed in intimate contact with the surrounding ground, which is the case with shotcrete, rock bolts and anchors, they will deform with the ground and attract load since the stresses in the ground are redistributed.

Dr. Sauer (1988) notes that the ring must be adequately supported within 1.5D of the face for a single tunnel in unstable rock conditions. However, for cohesionless and/or poor cohesion-ground, the three dimensional stress field has to be supported by an extension of the support shell ahead of the face, forepoling, or leaving an unexcavated wedge to support the face.

Kuesel (1987) points out that the dimensioning and details of the lining are barely related to stress considerations. He suggests that the first consideration should be given to the pore water. Therefore, if the lining must resist hydrostatic pressure, this ought to be governed by the lining design. In order to eliminate groundwater, either drainage or a waterproof membrane can be adopted. Kuesel's second consideration is constructability or compatibility of the lining design that is suitable for the expected ground conditions, which is mainly related to the stand-up time of the ground.

It is clear that the available closed-form solutions for circular tunnel analysis suggested by Muir Wood (1975), Peck et al. (1972), Mohraz et al. (1975), Sulem et al. (1987) are inappropriate for lining design of non-circular tunnels, NATM. Dr. Watson also states that

"They (closed-form solutions) may be used to a limited extent for the initial assessment of the maximum design loads on circular NATM primary linings, but they fail to consider the beneficial effect of stress relief ahead of the working face or the critical effect of the construction sequence on the development of temporary load conditions on the lining."

Therefore, the lining design and lining-medium interaction has been subjected to analytical and computational modelling. Ito and Hisatake (1981), for example, have conducted an analytical study to estimate earth pressures and displacements of steel supports and shotcrete in the New Austrian Tunnelling Method by means of considering the elasto-plastic behaviour of the lining. Leca & Clough (1992) analysed the shotcrete lining by the Finite Element Method. They proposed a simplified method for the preliminary design of the NATM tunnel support that estimates the lining thrusts and moments.

In summary, for shotcrete and secondary lining design the following should be considered:

i. Ground characteristics, such as strength and stand up time must be determined. The ground support interaction curve obtained accordingly.

ii. Ground water must be taken into consideration and required drainage or sealing should be maintained

a) If drainage is considered, the long-term stability of the drainage holes must be preserved and the quantity of these holes in respect to the water intake must be determined

b) When sealing is considered, water pressure must be taken into account in the design to calculate the loads on the lining. The long-term stability of the waterproof membrane should also be considered.

iii. Additional support elements such as rock bolts, spiling, lattice girders, steel welded mesh or steel fibre reinforcement should be used to increase the strength of the shotcrete. Shotcrete materials must be considered in the lining design to optimise time-dependent behaviour to answer the necessary flexibility and load bearing capacity.

iv. Monitoring of the stresses in/on the lining and the deformation must be provided.

v. Preliminary design of the initial lining should be conducted using available means of analysis such as empirical methods based on stochastic and/or observations, computational methods and small or full-scale physical models.

vi. The secondary lining is usually a precast concrete lining and they are placed after shotcrete has been applied. These concrete slabs are generally connected to each other with joints, which may be plane, or helical joints, concave/convex joints, convex/convex joints, and tongue and groove joints (Craig & Muir Wood 1978).

3.4.2 Geotechnical design criteria

Recalling NATM's main principle, the surrounding body of an opening is the main load-carrying component in its application. For optimisation of the load bearing capacity of the medium the characteristic ground-support reaction curve needs to be established. Therefore, the possible ground conditions should be interpreted from site and laboratory tests. The importance of these investigations are emphasised by NATM's proponents and the 1996 HSE report. It is also believed that the main cause of failure is unexpected ground conditions. Therefore, the ground investigation must be conducted thoroughly to ensure that there is no possibility of meeting any unexpected ground conditions (HSE 1996). The strength of the ground, stand-up time, pore water and drainage conditions, homogeneity and non-linearity of the ground, heave potential, time dependency or creep behaviour, discontinuities, the earth pressure at rest, magnitude of overburden pressure must be taken into account during these investigations. As a result, appropriate geotechnical design parameters must be chosen to fulfil analytical or computational preliminary design for eligible excavation patterns and geometry, and face advance in each round, as well as optimum support design.

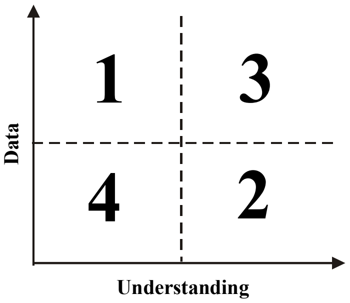

Figure 6 Classification of modelling problems (after Holling, quoted by Starfield 1988)

Starfield (1988) provides an insight into the methodology of rock modelling which can be related to soil mechanics. It has been noted earlier that geomechanical investigation of the ground, in which NATM will be used, is vital to the understanding of the modelling methodology for rock/soil. Figure 6 illustrates the classification of modelling problems. Holling (1978) introduces two axes one that indicates the quantity and/or quality of the available data and the other axis, shows the understanding of the problem to be solved (quoted by Starfield 1988). Then the region is divided into four quadrants. In region 1, there are enough data but little understanding so that statistics could be a proper tool. Region 2 indicates that there is good understanding but not enough data as in region 4 where the required data are unavailable or are not easily obtained. In region 3 both understanding and good data are available. Rock mechanics and the soil mechanics fall into regions four and two, which are data-limited problems. When laboratory and field measurements are main design considerations; the modelling of rock/soil by mathematical or computational methods was believed to be irrelevant or inadequate. Since then, this belief has moved towards computations. The Holling's classification explained here is the general methodology for geotechnical problems. However, this methodology can be regarded as being suitable for the geotechnical design of NATM tunnels as well.

3.4.3 Design of NATM applications in soft ground

In the case of soft ground applications, especially in soils, NATM applications are relatively recent. The main concern pointed out by Muller (1978) is that the shotcrete ring must be closed as early as possible in any soft ground application of NATM. One of the reasons for rapid ring closure is to prevent surface buildings suffering damage from settlement. Another reason is that the shorter stand-up time of soft ground is due to the bond between soil particles being weaker and cohesion is also lower than for rocks. In the near surface soft ground case, the in-situ stress will be relatively low, the ground relatively weak and unable to support redistributed loads. Brown (1990) has reported that

"…In a near surface tunnel excavated in soft ground, it will be generally necessary to close the invert quickly to form a load-bearing ring and to leave no section of the unexcavated tunnel surface unsupported even temporarily…"

It is also important that the length of the unsupported span must be left shorter compared to tunnelling in rock. In addition, the stability of the working-face must be maintained. To avoid any collapse, the geometry and the size of the excavation section in one round should be optimised accordingly.

The ICE report (1996) on the design of NATM tunnels in soft ground, with particular reference to London Clay, emphasises the same point explained above as the sprayed concrete linings of significant stiffness, i.e. a closed ring of sufficient thickness must be installed as quickly as possible to control the settlement in urban areas. In addition, this report introduces a diagrammatic representation of the design for soft ground applications of sprayed concrete linings as illustrated in Figure 7.

According to the proposed design routes, the analytical route helps dimensioning of the SCL for the foreseeable conditions. The monitoring of the performance of the lining leads to validation of the design. This also allows the designer to enhance safety and allocate soundly based reactions to unforeseen circumstances. The other empirical route allows greater flexibility during construction in order to determine the shotcrete thickness directly from the observed actual ground conditions. However, the empirical route essentially depends on past experience in similar conditions to determine the thickness of the linings required (ICE, 1996).

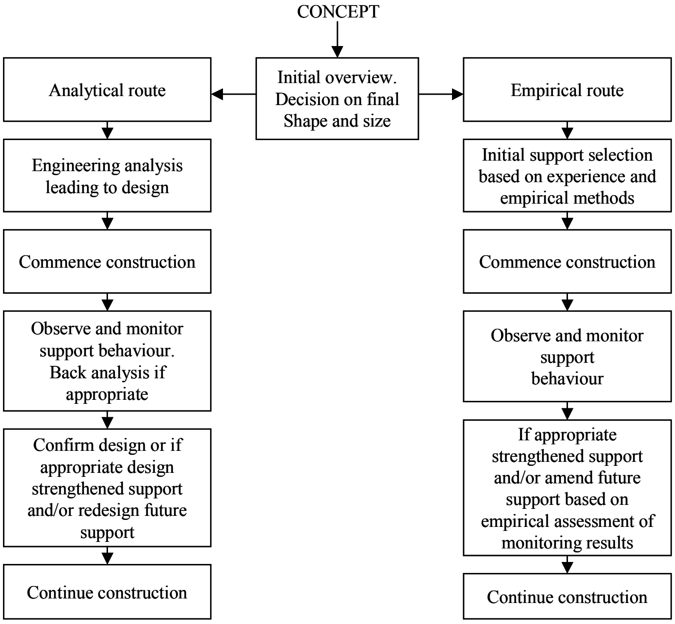

Figure 7 SCL design routes (after ICE 1996)

3.4.4 Design for Safety of NATM tunnels produced by the HSE

Relatively recent soft ground NATM application has brought about collapses some of which produced catastrophic damage to surface buildings, and some of which caused environmental impact by creating large holes in urban areas. Thus, the safety regulations for underground works have limited the design consideration. After three parallel tunnels, which were being constructed as part of the Heathrow Express Rail Link in London Clay, collapsed, The Health and Safety Executive (HSE) (1996) prepared a report viz. Safety of New Austrian Tunnelling Method (NATM) Tunnels. They have proposed a number of safety measures and design criteria before, during, and after a construction of NATM tunnels. These can be summarised as follows:

- Ground investigation:

This investigation must be carried out to reduce the likelihood of encountering unexpected geological conditions.

- Engineering technology:

The technological improvement in tunnelling equipment must be considered and new technological progress should be employed to take advantage of them. Also, a comparison between new and previous technology should be undertaken to assist in selection of the most appropriate technologies. Moreover, universities, research groups can contribute to the evaluation and investigation of new and/or untried methods of working.

- A risk-based approach to NATM design:

In tunnel design and construction, there has always been some degree of uncertainty. This issue is significantly related to the NATM. Thus, a risk-based approach to design and management is required (more details are given in HSE, 1996).

- Monitoring:

There are two essential objectives of monitoring; design monitoring and construction monitoring. Monitoring should be undertaken to ensure safety of design and construction. Data assessment and interpretation must be done by the geological/geotechnical specialists, tunnel designers, construction managers (including quality and safety managers)

- Stability of the tunnel heading:

The tunnel heading is the part of the tunnel that is excavated ahead of the completed support ring. Most failures occur during or soon after excavation of this part of the tunnel. Therefore, to secure the safety of those who work within the tunnel and in buildings, structures and utilities above the tunnel, stability of the face must be maintained using additional supports such as forepoles, faster excavation, draining ground water and reducing the face size or advance per round.

- Ground settlement control measures:

To reduce the risk of damage to surface buildings, settlement due to tunnel excavation must be controlled by proper construction of the tunnel heading, under-pinning existing structures, and compensation grouting.

- Sprayed concrete lining design:

The physical properties of the shotcrete such as thickness, additional reinforcement, must be designed according to the project requirements. Necessary computational design as well as small-scale trial works and past experiences should be considered.

3.5 General NATM excavation patterns

A number of different NATM tunnel sizes, geometry, and excavation patterns have been adopted in a range of geological conditions. In most cases, especially in soft ground, it is not applicable to excavate the full tunnel face. Hence, the excavation face is usually divided into small cells that will help the ground stand until completion of the lining. Generally, excavation is carried out in six or more steps depending on the size and the geometry of the tunnel. Figure 8 illustrates a typical main cross-sectional geometry for a NATM tunnel proposed by Rabcewicz (1965). The shape of the tunnel is different from conventional circular tunnels. The Roman numbers indicate the excavation order and subsequently applied support elements. The first step is the excavation of the top heading (I), leaving the central part to support tunnel face. Then, the auxiliary lining (shotcrete) II is formed and followed by removing the top central portion (III) subsequently excavation of left and right walls (IV).

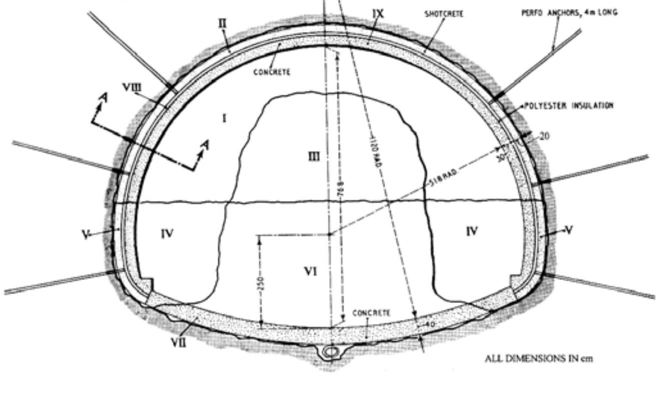

Figure 8 Typical main cross-sectional geometry for a NATM tunnel proposed by Rabcewicz (1965)

The fifth step is the application of shotcrete with additional reinforcements (V) followed by excavation of a bench (VI). Finally, the invert is closed with concrete (VII) following the installation of a waterproof membrane (VIII) and concreting of the inside lining (IX).

4 NATM APPLICATIONS IN EUROPE

The NATM was first used for tunnelling in unstable ground for the Lodano-Mosagno tunnel of the Maggia-Electric Scheme in Switzerland (1951-55) (reported by Sauer et al. 1973). As a temporary support, shotcrete was applied to the walls of the tunnel. Widespread recognition of NATM followed Rabcewicz's article published in English in 1964. NATM was used for the Schwaikheim Tunnel in Germany in 1964 (quoted from Bowers 1997). This was followed by a series of Alpine NATM tunnels such as Arlberg Expressway tunnel constructed between 1973 and 1978. A significant part of the Vienna metro was built in soft and difficult water bearing ground using NATM (Murphy et al. 1994).

During the 1970s and 1980s NATM has been extensively used particularly for the metro systems in Bochum, Frankfurt, Munich, Nuremberg, and Stuttgart in Germany. Soft ground NATM tunnelling was for the first time applied to the Frankfurt/Main metro in Germany in soils of extremely low strength (reported by Sauer et al. 1973). Other soft ground NATM tunnels were for the Hanover-Würzberg high-speed railway line, which is 120 km long and runs through 65 twin-track bored tunnels where a series of major collapses occurred, almost one every 10 km (reported by Wallis 1990).

Elsewhere in Europe, tunnels include the 160 m² cross-sections on the Bilbao metro (quoted from Bowers 1997), and 20 m wide × 9.8 m high Montemor Tunnel, Lisbon (reported by Wallis 1995), 100 m² Ayaş tunnel near Ankara in Turkey (Tümer & Türdü 1985), the Palabutsch tunnel near Graz passes through the Alps as a traffic tunnel between Germany and Yugoslavia (Mussger et al. 1990), and the Ujo Tunnel which is 5.4 m wide and 6.0 m high, as a railway tunnel in Spain (Leiria 1980) are amongst the many other tunnels constructed using the NATM. The first appearance of NATM in UK was for access tunnels for a gypsum mine at Barrow-upon Soar (Deacon 1988). In 1987, NATM was extensively used during the construction of the Channel Tunnel. The next application was the Round Hill road tunnels in the Lower Chalk. The first application of NATM in London Clay was under Heathrow Airport, one of the busiest airports in the World (Bowers 1997).

4.1 HSE report of failure incidents for NATM in the World

Some of the NATM applications in Europe have been introduced earlier where many of these applications were faced with collapses not only in Europe but worldwide. Providing case studies of NATM collapses is needed to find out the reasons behind these NATM failures. Therefore, the list of worldwide collapses for the NATM is given in Table 2.

As can be seen from Table 2, the worldwide reputation of this method has suffered from unsuccessful applications. Table 2 also gives the location of the collapses in the tunnel.

Type 'A' failures, heading collapses, occurred in the area between the tunnel face and the first complete ring of the sprayed concrete lining, and the type 'B' failures occurred in the region in which sprayed concrete lining is complete (Figure 9). 'C' type of failures occurred in a different part of the tunnel which are located far away from where A and B type of collapses occurred such as collapses at portals or at breakouts from vertical construction shafts

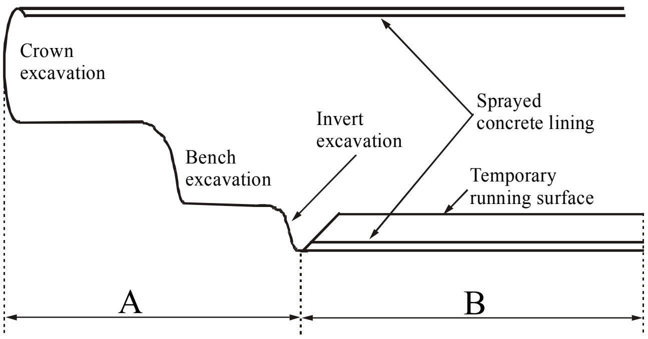

Figure 9 Location of collapses (adapted from HSE 1996)

4.2 Failure patterns for NATM

There are a number of collapses and failures of NATM tunnels that have lead to human death and injury. These collapses brought about serious damage to public buildings and infrastructure. According to the HSE report, 39 major incidents some of which are given in Table 2, have occurred during the 30 years since NATM was first introduced.

The increase in the incidents reported is attributed to a number of factors as follows:

- There are inherent problems with NATM tunnel construction
- Hazards are not being adequately identified, managed and controlled
- There is over-confidence in the method

Table 2 Worldwide NATM Collapse incidents (reproduced from HSE report, 1996)

Date and location of Collapses	Location	Project	Urban or Rural	Consequences
October 1973, A*	Paris, France	Rail	?	?
13 November 1984, A	Landrücken tunnel, Germany	Rail	Rural	?
1984, A, B*	Bochum Metro, Germany (1)	Rail	Urban	Urban disruption
17 January 1985, A	Richthof Tunnel, Germany	Rail	Rural	?
1985, A	Bochum Metro, Germany (2)	Metro	Urban	Urban disruption
August 1985, A	Kaiserau Tunnel, Germany	Rail	Rural	
17 Feb. 1986, A	Krieberg Tunnel, Germany	Rail	Rural	Large surface damage
Before 1987, A, C	Munich Metro, Germany (6 major collapses)	Metro	Urban	Urban disruption, excavator buried
8 Jan 1989, A	Karawanken tunnel, Austria/Slovenia	Road	Rural	
27 Sep. 1991	Kwachon Tunnel, Korea	Metro	Rural	
17 November 1991, A	Seoul Metro, Korea	Metro	Urban	Fractured gas main
27 November 1991, A	Seoul Metro, Korea	Metro	Urban	Substantial urban disturbance
1992	Fungata Tunnel, Japan	Road	Rural	
12 Feb. 1992, C	Seoul Metro, Korea	Metro	Urban	Utilities broken, traffic problem
30 June 1992, A	Lambach Tunnel, Austria	Rail	?	
7 January 1993, A	Seoul Metro, Korea	Metro	Urban	Road disruption
2 February 1993, A	Seoul Metro, Korea	Metro	Urban	Loss of construction plant
Feb/March 1993, A	Seoul Metro, Korea	Metro	Likely urban	
March 1993, A	Chungho Tunnel, Taipei, Taiwan	Road	Rural	
November 1993, A	Road tunnel in Sao Paulo, Brazil	Metro	Urban	Huge Urban disruption
30 July and 1 Agust 1994, A	Montemor Road tunnel, Portugal	Road	Urban	
August 1994, A	Galgenberg Tunnel Austria	?	? Rural	One death
20 Sept. 1994, A	Munich Metro, Germany	Metro	Urban	4 deaths and 27 injuries, urban disruption
21 October 1994, C	Heathrow Airport London	Metro	Urban	Urban disruption

*See Figure 7.

- There is more open reporting of failures
- NATM is increasingly being used in more demanding environments
- NATM is being used by those unfamiliar with the technique

Figure 10 illustrates the type of collapses that have occurred in headings. These are as follows: a) Crown failures where soil flows into the tunnel b) Local face failures where a part of the working face runs in to the tunnel c) Bench failures where a part or the entire of bench slides transversely or longitudinally into the tunnel d) Full face failures in which face, heading and bench flow into the tunnel e) Washout failures f) Pipe failures

Other types of failure that occurred are failures of the lining before and after ring closure, and both before and after ring closure, bearing failure of the arch footings, failure due to horizontal movement of the arch footings, and the failure of the side of the gallery wall which took place after closure of the lining ring. Shear failure, compressive failure, combined bending and thrust failure and punching failure of the lining came about before and after ring closure.

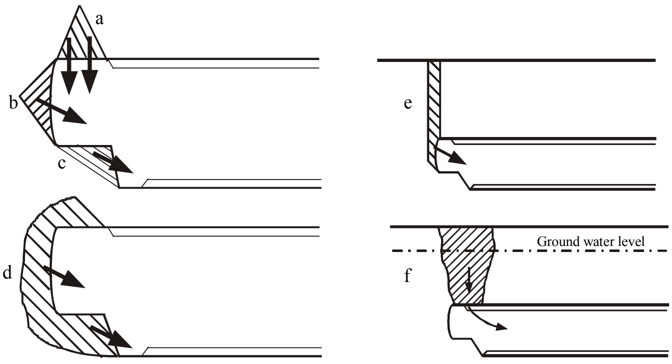

Figure 10 Ground collapses in the heading of NATM tunnels (adapted from HSE 1996)

Causes of these collapses are reported by the HSE (1996) as follows:

- Unpredicted geological causes
- Planning and specification mistakes
- Calculation or numerical mistakes
- Construction mistakes
- Management and control mistakes

4.3 *A particular NATM failure case, the collapse at Heathrow Airport*

The Heathrow Express (HEX) Station tunnel which collapsed on the 21 October 1994 lead to headlines such as “Britain’s worst civil engineering disaster in modern times” (Bishop 1994). The tunnels at Heathrow were excavated as part of the £235M express rail link to Paddington Station, central London. The HEX Station tunnels comprised two parallel platform tunnels constructed on either side of a concourse tunnel from an existing shaft (Figure 11). As discussed earlier, in many cases, the occurrences of NATM collapses typically take place in the working face area. On the other hand, the HEX collapses were initiated by the failure of the thin support shells in one of the platform tunnels where it connected to an adit (Oliver 1994a). Another comment made in Tunnels & Tunnelling (1994) suggests that "…Indeed, a peculiarity of the collapses at Heathrow is that they did not occur at the face and may well have been initiated where repairs to the invert of the concourse tunnel were being carried out…"

More than 10,000 m^3 of concrete was pumped into the tunnel complex to stop further progressive collapses. As a precaution, car parks number 3 and number 5 were evacuated, but Cambourne House, the site headquarters building, tilted on its foundations (Oliver 1994b). Damage to the surface buildings caused by this massive ground loss brought about many speculations in the media as well as meticulous investigations by the Health and Safety Executive.

According to Winney's report (1994), Mike Savage, geotechnical instrumentation specialist, claimed that

"Ground measurement arrays at Heathrow should have given days of warning about the collapse…"

In fact, the danger was spotted two hours before the catastrophe and unfortunately, they were not interpreted as claimed by Mike Savage.

Another recent declaration made by Jonathan Allen, British Airports Authority plc (BAA) area manager, claimed that shotcrete in the construction of the invert has the thickness of 50mm instead of being 300mm (reported by Thompson 1999a). As a result, the main contractor Balfour Beatty, and sub-contractor Geoconsult were prosecuted by the HSE (reported by Thompson 1999b).

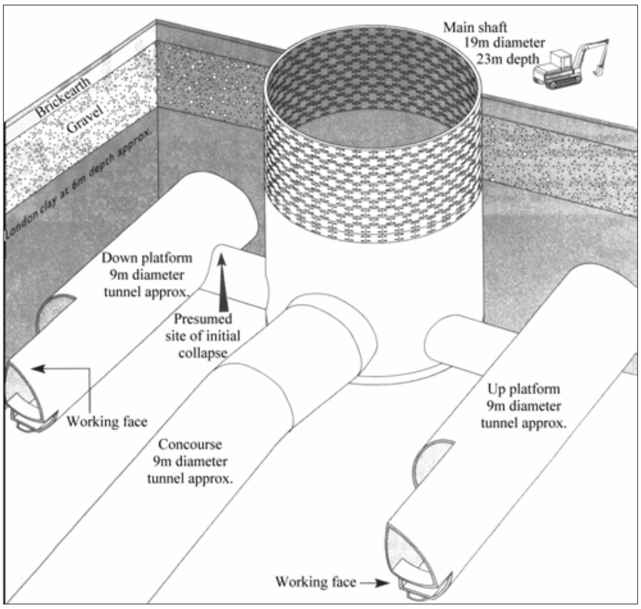

Figure 11 Sketch of the collapsed system at Heathrow (after Oliver 1994a)

In the aftermath of the collapse, the HSE and the ICE have published special reports providing an insight into the origin of NATM and the causes of NATM collapses. These have already been discussed in the previous sections.

5 DISCUSSION

Detailed descriptions of the NATM, its origin, design considerations, failure mechanisms, and causes of failures as well as NATM support design considerations have been revised in this paper. Rabcewicz and other proponents of NATM emphasised that the main objective of NATM is to use the ground as a load-bearing support element to the maximum extent possible. Prof. Kovári (1994) claimed that the role of the ground as a support member is a distinguishing feature for not only NATM, but all means of tunnelling. Moreover, carrying on his criticism, he stated, "…Where NATM is concerned, it is not the construction that is flexible, but rather the definition of NATM, which can be stretched in an arbitrary manner."

From the first time NATM was introduced, up until now, many criticisms, and new definitions have been made by digging the original concepts out and denying that NATM is not a new technique, and so on. On the contrary, during this literature survey, numerous tunnels constructed in accordance with the NATM philosophy were found. This implies that whatever critics say and the conflicts that have arisen; the NATM philosophy runs as good as any other tunnelling method. For instance, The North Downs tunnel as a part of the Channel Tunnel Rail Link (CTRL), the first large NATM tunnel up to 96.2 m^2 gross free area, commenced using NATM philosophy after Heathrow tunnel collapse (Watson et al. 1999). This shows that NATM or the Sprayed Concrete Lining method has overwhelming advantages when appropriate design procedures are employed taking into account the potential dangers. These advantages can briefly be listed as follows:

1. Flexibility to adopt different excavation geometries and very large cross sections.
2. Lower cost requirements for the tunnel equipment at the beginning of the project.
3. Flexibility to install additional support measures, rock bolts, dowels, steel ribs if required.
4. Easy to install a waterproof membrane.
5. Flexibility to monitor deformation and stress redistribution so that necessary precautions can be taken.

6. Less overall support cost by ensuring that support is sufficient for the loadings and ground conditions without being excessive.
7. Providing a good contact surface between support and ground by using shotcrete.
8. Easy to install primary support, i.e. shotcrete.
9. Flexibility to use in various ground conditions.

In addition, the understanding of the NATM concepts by the tunnelling crew is an important requirement for implementing this tunnelling philosophy correctly. Otherwise, failure of NATM tunnels is inevitable. Monitoring and optimising the ring closure time is of crucial importance for successful application of NATM as well.

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