NATM IN SOFT-GROUND: A CONTRADICTION OF TERMS?

When the New Austrian Tunnelling Method (NATM) is mentioned, it often means many different things to even experienced tunnelling engineers. The scene has more recently been complicated by new terms introduced to reflect certain aspects of NATM. Victor Romero, an associate with US-based engineering practice Jacobs Associates gives his views on NATM and its application to soft-ground tunnelling, and dispels some misconceptions about this sometimes controversial topic.

'New Austrian Tunnelling Method'. 'Sequential Excavation Method'. 'Sprayed Concrete Lining'. Not even the tunnelling industry can give a unified name for a tunnelling method pioneered by the Austrians in the later half of the twentieth century. Furthermore, we are seeing increased use of this method in the US, particularly in soft-ground conditions. In order to better define the method, it is helpful to look at its history and use in both design and construction.

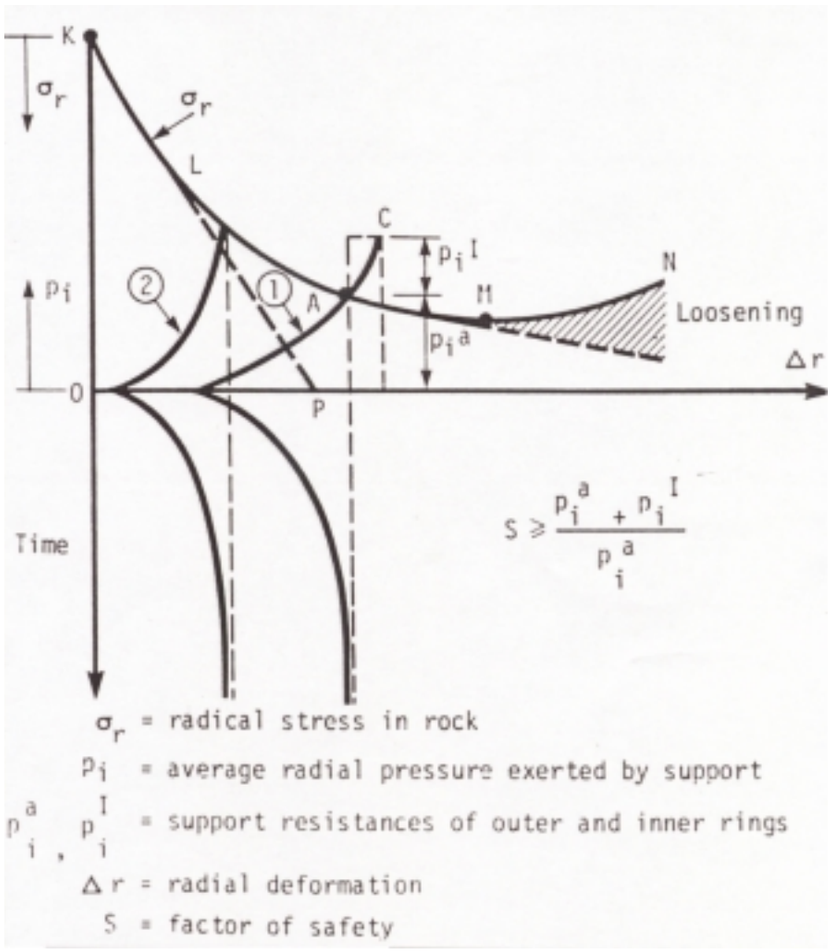
NATM in perspective

As defined by the Austrian Society of Engineers and Architects, the NATM "…constitutes a method where the surrounding rock or soil formations of a tunnel are integrated into an overall ring-like support structure. Thus the supporting formations will themselves be part of this supporting structure." In world-wide practice, however, when shotcrete is proposed for initial ground support of an open-face tunnel, it is often referred to as NATM. The term NATM with reference to soft ground, however, can be misleading.

As noted in a very thoughtful article by Emit Brown[1], NATM can refer to both a *design philosophy* and a *construction method*. Key features of the NATM design philosophy are:

- The strength of the ground around a tunnel is deliberately mobilised to the maximum extent possible.
- Mobilisation of ground strength is achieved by allowing controlled deformation of the ground.
- Initial primary support is installed having load-deformation characteristics appropriate to the ground conditions, and installation is timed with respect to ground deformations.
- Instrumentation is installed to monitor deformations in the initial support system, as well as to form the basis of varying the initial support design and the sequence of excavation.

Key features of NATM construction methods are:

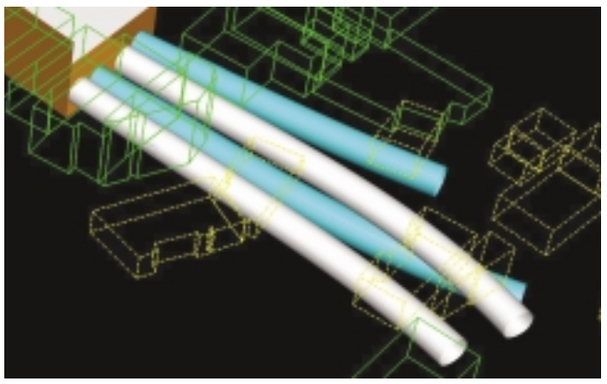


Generic ground reaction curve that is often the basis of NATM design (after Brown, 1981[1])

- The tunnel is sequentially excavated and supported, and the excavation sequences can be varied.
- The initial ground support is provided by shotcrete in combination with fibre or welded-wire fabric reinforcement, steel arches (usually lattice girders), and sometimes ground reinforcement (e.g., soil nails, spiling).
- The permanent support is usually (but not always) a cast-in-place concrete lining.

It should be noted that many of the construction methods described above were in widespread use in the US and elsewhere in soft-ground applications before NATM was described in the literature. In current practice, for soft-ground tunnels which are referred to as NATM tunnels, initial ground support in the form of shotcrete (usually with lattice girders and some form of ground reinforcement) is installed as excavation proceeds, followed by installation of a final lining at a later date.

Simply speaking, soft ground can be described as any type of ground requiring support as soon as possible after excavation in order to maintain stability of the



Example of multiple, interacting tunnels where numerical modelling is appropriate for design

excavation. For tunnels in dense urban areas, limiting settlement is of paramount importance to avoid damage to overlying structures. In order to limit settlement and ensure worker safety, most soft ground tunnels employ the following measures:

- Excavation stages must be sufficiently short, both in terms of dimensions and duration.
- Erection of the 'full ring' of initial ground support must be completed immediately after excavation.

It should be noted that the major difference between the NATM design philosophy and traditional soft ground tunnel construction measures is that deformation of the soil is not easily 'controlled'. Therefore, it can be concluded that the excavation and support planned for sequentially excavated, shotcrete-lined tunnels in soft ground utilises NATM construction methods but not necessarily NATM design methods.

NATM for soft ground?

In soft-ground tunnelling, safety dictates that the ground support be placed immediately after excavation. As long as the ground is properly supported, NATM construction methods are appropriate for soft-ground conditions. However, there are cases where soft-ground conditions do not favour an open face with a short length of uncompleted lining immediately next to it, such as in flowing ground or ground with short stand-up time (i.e., failure to develop a ground arch). Unless such unstable conditions can be modified by dewatering, spiling, grouting, or other methods of ground improvement, then NATM may be inappropriate. In these cases, close-face shield tunnelling methods may be more appropriate for safe tunnel construction.

A 'black box' for design?

Is a computerized 'black box' appropriate for NATM design? By 'black box' I mean a numerical model that presumes to calculate stresses in the ground and tunnel support (i.e. lining). Traditionally, this has been done with finite element or finite difference methods. As with any computer modelling, the answers are only as good as the geotechnical input parameters and the constituent models used for analysis. The constituent model theories should not be a mystery, and both the Engineer and the Client (be it an owner or a contractor) should clearly understand the limitations of computer modelling. Most importantly, field observations and measurements should be

used to confirm assumptions and calibrate future models.

Notwithstanding the above, numerical modelling is a useful tool for design of sequentially excavated, shotcrete-lined tunnels in soft ground. In particular, numerical modelling is useful where interacting tunnels, unusual geometries, or adjacent structures are present. We prefer to use the software FLAC or PLAXIS for numerical modelling of tunnel linings in soft-ground. However, if a shotcrete-lined tunnel has a section that is nearly circular or oval with no irregularities, and if there are no adjacent surface or subsurface structure interacting with the tunnel, then traditional ground-lining interaction methods can be used for design. Indeed, the closed-form ground-lining interaction equations provide a prudent check on numerical modelling.

So do you need a black box? If you don't know what the theory behind the black box is and cannot correlate the analysis with tunnel behaviour in the field, then you should not rely on a black box for *any* type of tunnel design. However, if you are using a tested program with good constituent models and know its limitations, then programs such as FLAC can be useful design tools. But be sure to verify the results in the field and with a traditional ground-lining interaction analysis, if appropriate.

Instrumentation and monitoring?

As noted above, instrumentation and monitoring play a key role in verifying design assumptions and calibrating numerical models. More importantly, however, monitoring serves to alert the designer and the constructor if the lining is not performing as intended, or is in danger of collapse. In this respect instrumentation of NATM construction is no different from other types of geotechnical construction. Therefore the tried and true rules of thumb for geotechnical instrumentation apply to NATM, namely:

1. Predict mechanisms that control behaviour, and define the geotechnical questions to be answered.
2. Define the purpose of instrumentation, and select parameters to be monitored.
3. Predict magnitudes of change, and determine threshold limits and remedial actions.
4. Assign tasks and responsibilities.
5. Select instruments and locations.
6. Devise methods to ensure correctness.
7. Plan data collection, processing, presentation, interpretation, and reporting.

If you get these steps in a systematic instrumentation and monitoring approach correct, and there is good communication between the Engineer and the Contractor, then you have a fighting chance of getting good data that can be relied upon, in order to make decisions during construction.

Short headings and spiles being used to control unstable ground

Shotcrete used successfully for initial support in a soft-ground tunnel

Tunnel collapses?

Unfortunately there have been several collapses or other stability failures of NATM projects around the world including, most recently in Turkey and the US. Perhaps the most famous is the Heathrow Airport collapse in October 1994, which triggered a thorough review of the NATM by the British Health and Safety Executive (HSE). In a 1996 report[2], the HSE examined 39 NATM failures, categorising the location (in the tunnel) of the failure. In most cases, the failure was a result of heading collapse. Broadly speaking the causes of these failures were varied, from unanticipated geologic conditions, to design errors, to construction quality problems, to poor management. Nevertheless NATM failures, or for that matter any tunnel failure, have one thing in common: most are caused

by human error. It's not the fault of the method, but misapplication of the method.

What do we call it?

On the question of terminology, it is difficult to cover all aspects of the method. The British have proposed SCL, short for Sprayed Concrete Linings (Institution of Civil Engineers, 1996[3]). However, the term 'sprayed concrete' is not very common in the US and many other parts of the world, where shotcrete is the commonly used term for pneumatically applied concrete. Moreover, shotcrete is used in different types of tunnels (rock and soft ground) and for many different applications (as lining, lagging, surface protection, etc.). Since the use of shotcrete lining in soft-ground tunnels is almost always associated with sequential excavation, my preferred terminology is SEM, for Sequential Excavation Method. The use of SEM as standard tunnel terminology also highlights the fact that this is a *construction* method, rather than a *design* method. I would, however, recommend keeping NATM as terminology for the design method used in rock tunnels when support installation is timed to a ground reaction curve.

References

[1] Brown, E.T. Putting the NATM into perspective. *Tunnels & Tunnelling*, November 1981.

[2] Health & Safety Executive. Safety of New Austrian Tunnelling Method (NATM) Tunnels, A review of sprayed concrete lined tunnels with particular reference to London Clay, HSE Books 1996.

[3] Institution of Civil Engineers. Sprayed concrete linings (NATM) for tunnels in soft ground. ICE design and practice guide, Thomas Telford Publishers, London, UK 1996.

Closing the ring quickly behind the bench, as shown in this photo, is key to preventing lining instability

Acknowledgement

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If you, the readers, have views on the terminology most appropriate to 'NATM' sequential excavation, shotcrete linings or observational methods please share them with other readers in the form of a Letter to the Editor of World Tunnelling*, or submitted articles for longer arguments or examples of method deployment.*

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