Fallacies in NATM/RSST shotcrete supported tunnelling

Detailed independent analyses of all data indicate that the dominant published premises of so-called NATM optimisations based on convergences are illusory and misleading, writes Victor F B de Mello *of Brooklin, São Paulo, Brazil, in Part 1 of his paper. They divert attention from 'shake' movements and rapid shotcrete (plus bolt-and-rib) support which otherwise guarantee against rigid-brittle collapses.*

The rapid shotcrete supported tunnelling method (RSST), publicised as NATM, has been successful in countless tunnel kilometres, fostering fast-growth marketing. The acronym NATM should be avoided because it obscures the fundamentals on which success is based. It allows the occasional traumatic spot failures which generate heated debate to be exaggerated.

The key selling point of RSST is flexibility — not only of the primary lining but, more to the point, of expert decision based on much vaunted on site engineering.

The mystique surrounding NATM promotes the confusion arising from the division of responsibility between the specialist consultant and the full time on site supervisor at a time when speedy action on the part of the contractor is imperative to deal with any pending emergency.

Flexibility and on site engineering based on self appraisal are prerequisites for success. But the rhetoric of NATM allows faith to win out over experience, logic, reflection and the updating of knowledge. Whenever there is a vacuum, 'fools rush in where angels fear to tread'. Hoek, writing in 1994, says:

"One of the major problems in designing underground openings is that of estimating the strength and deformation of the in-situ rock mass. In the case of the jointed rock masses, an evaluation of these properties presents formidable theoretical and experimental problems." And, regarding the Hoek and Brown rock classification criterion: "Our empirical criterion and our estimates of the input parameters were offered as a temporary solution to an urgent problem... I am alarmed to see the criterion being applied to problems we did not even dream about when we made those desperate estimates years ago."

The importance of emphasising RSST instead of NATM is that by being open to a more realistic diagnosis of primary vs. secondary problems it is possible to facilitate rapid solutions which can then be transmitted and made public. RSST emphasises the importance of speed in defeating deficiencies in standup time and primary shotcrete and bolts etc with its complex rheology of stress-strain/strength/time permitting:

- a short period of flexibility to enhance some rock-shotcrete interaction;
- followed by a rapid set into a rigid-brittle high strength layer for structural support.

Case history

This case refers to the investigation of a fairly inconsequential failure in a highway tunnel executed by drill+bast, with half-section sequentiai excavation.

The rock is part of the archean granitic-gneiss Brazilian shield and is moderately fractured, with joints weathered to the point of being smeared with clayey veneer. While the half-section was driven, geological features were surface mapped separately by three geologists (designer, owner and instrumentation company). Convergence measuring pins were set up at roughly 20m spacings and continually monitored. Other monitoring measures included piezometers, surface settlement points and some deep settlement telltales.

With regard to space restrictions, reference is limited to convergence measurements, viewed as the basis for adjustment of the characteristic curve of the NATM method. The blatant fact was that nobody could set any quantitative boundaries on accept/reject criteria for the various instrumented measurements. Often the nominal limits set, for the sake of appearances, were greatly overshot without any decision or action having been taken. In general, nothing unfavourable occurred. Attention is concentrated on Stations 142 and 143, which suffered ulterior collapse, and on convergences of Chord C (Fig 1) in that stretch and elsewhere where comparisons are significant.

During the half-section excavation, at

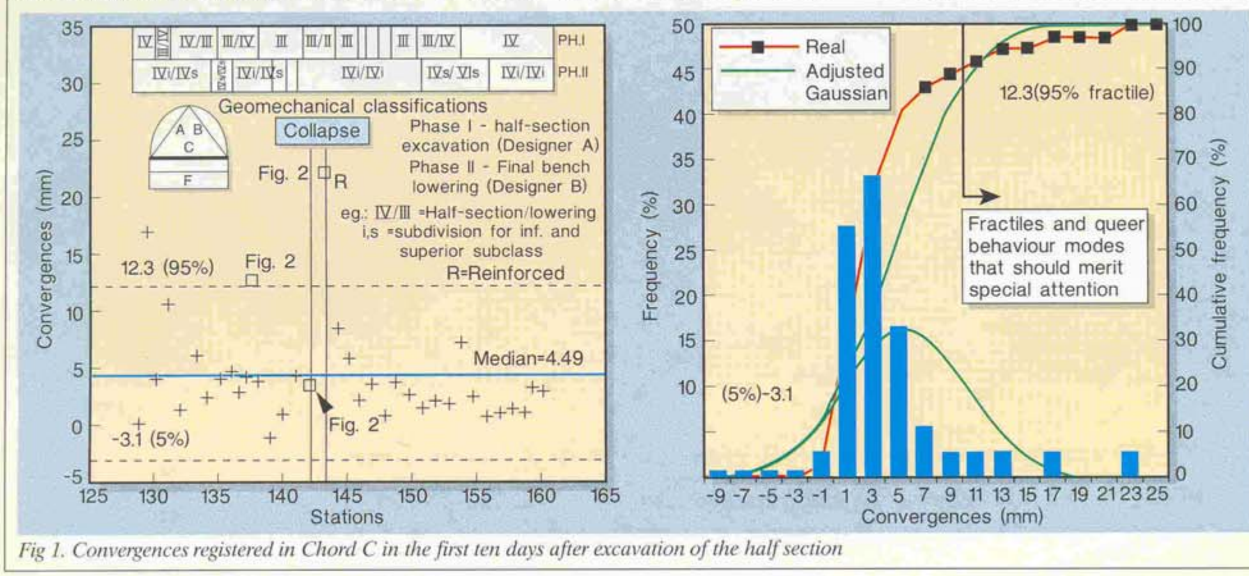
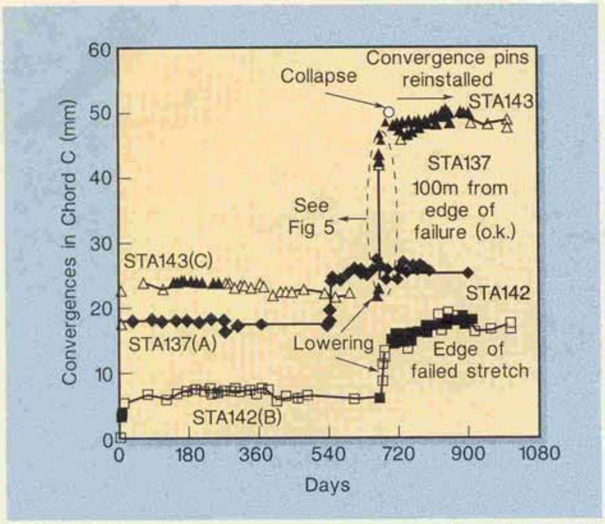


Fig 1. Convergences registered in Chord C in the first ten days after excavation of the half section



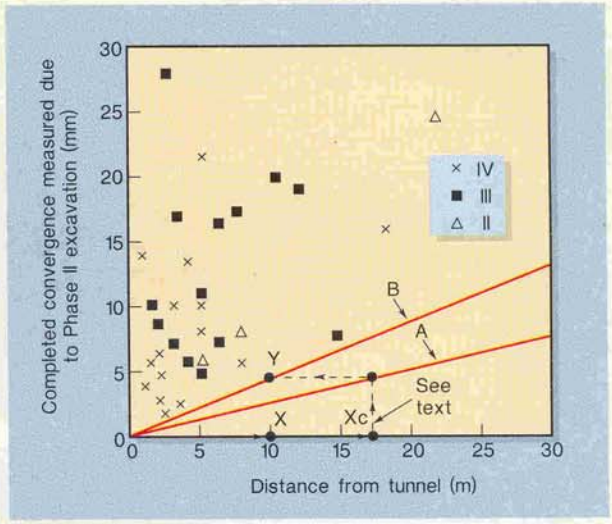


Fig 2 (left). Complete convergence measurements of three chosen sections. Fig 3 (right). Comparison of complete and incomplete convergences.

Station 143, action was taken because of the unusually high convergence observed — roughly three per cent fractile (Fig 1) — having an accelerating tendency. it was concluded that shotcrete confinement at the foot of the support arch had to be reinforced. Within three days after reinforcement, the desired stability was recorded.

After the half-section was completed with its 200mm primary shotcrete lining, construction was halted for various reasons for over 18 months. The project thus profited by an enviable opportunity for behaviour monitoring.

Meanwhile, another tunnel had suffered an embarrassing failure which compelled the contractor to double his assurance by engaging a second design company (B) to revise every detail, past and future. Rock classifications were revised (Fig 1) and several stretches were specifically reinforced with bolts, anchors and cement grouting. Thereafter, the so-called NATM method continued to be applied using the safest of the rock classification criteria, superimposing designer B on designer A and earlier participants which also continued to work on the project.

During the two years that intervened, Chord C at Station 143 showed a very small tendency to accumulate a total divergence of 2.5mm in the first four months, followed by indisputable stabilisation, all of which was taken as reassuring.

During excavation of the half-section there is a delay of a day or two until installation of the convergence points permits the first readings to be taken. During Phase II excavation, however, the Chord C measurements permit accompanying all effects. Fig 2 presents the complete convergence measurements of three chosen sections.

Design and monitoring indications were considered satisfactory, and tunnelling proceeded routinely. Roughly 20 days after passing the section, and ten days after completion of the tunnel (excavated from

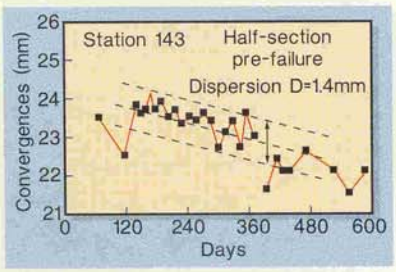


Fig 4. Dispersion and convergence trends.

both ends and terminating about 50m ahead of the ill fated stretch of B,C in Fig 2, the collapse occurred.

Analyses and conclusions

Convergence measurements receive great attention as though they should reflect deformations of the geomechanical body interacting in a manner that can be analysed structurally with the shotcrete layer.

First, there is a zero correction to be made for the half section convergences measured. Under postulated 'experience', a multiplying factor of 1.75 was considered for transforming measured convergences into the desired nominal complete convergences pertaining to the Phase I half section excavation.

In Fig 3, the two straight lines A and B show how to transform elastic convergences for comparison and analysis: starting from the incomplete actual measured point x due to Phase I, multiplying on the abscissa by 1.75 to obtain the hypothetical corresponding complete value Xc, then multiplying by 0.25 to obtain the ordinate Y of the presumed complete elastic convergence for the respective Phase II; thereby transplanting back to obtain the coordinates (x,y) on line B. The analysis in Fig 3 starts from the following hypotheses:

- complete convergence is the sum of blasting shake plus stress release; and
- shake should not cause divergence.

Important conclusions to be derived

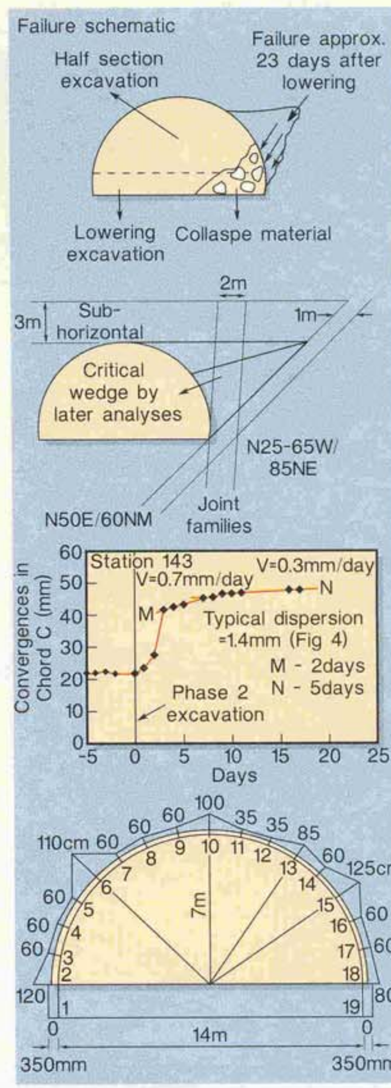


Fig 5. Diagrams show, from top to bottom: the typical overbreak, failure section and velocities of convergences to use as a basis on which to make decisions.

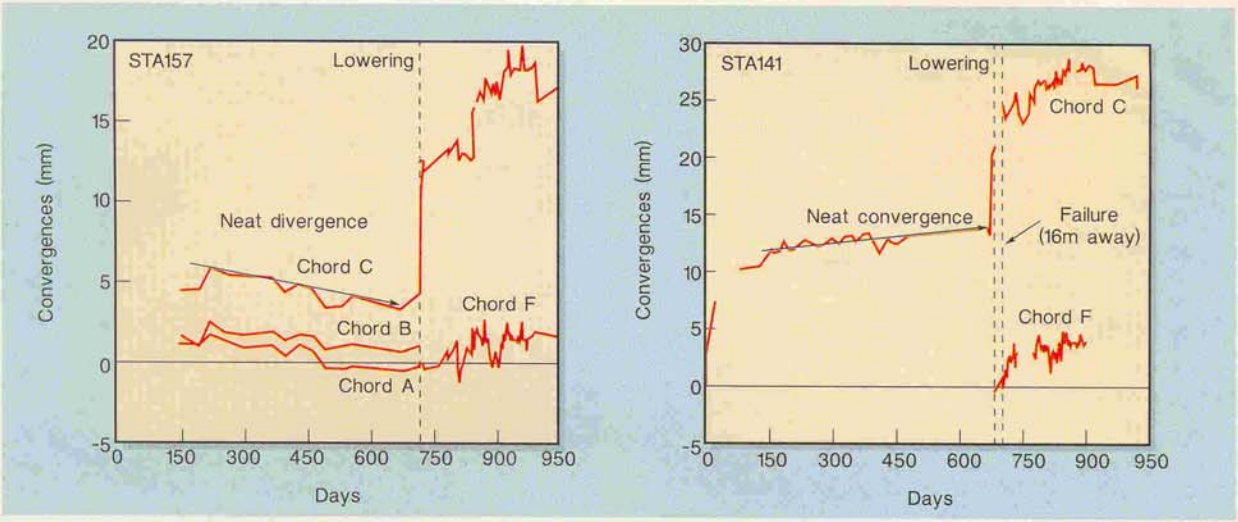


Fig 6. These diagrams pose further questions regarding indications observed with respect to movements.

from this analysis are:

- by far the greatest convergence was due to rock settlement after blasting shake; and
- there was no evidence of relationship with elastic stress release and there was virtually no connection with rock class. The importance of controlled blasting becomes salient and, ipso facto, the predominance of differentiated behaviour of a disturbed rock collar interacting with the shotcrete layer.

Dispersions and deformation

Principal conclusions for on site engineering decisions are to be derived from three distinct displacement measurements: surface settlements; deep telltale (T) settlements of points within the mass above the tunnels; and convergence measurements.

Reverting to convergence monitoring (Fig 4), an obvious impression would be that dispersions limited to the order of 2mm should be satisfactory for a 15m diameter tunnel. The nub of the problem is, however, that decisions have to be taken in hours or a day or two at most. In Fig 4 (taken as typical among scores which are similar) it is evident that a behaviour trend is only confirmed beyond the irrelevance of dispersions in periods of 21 days to 94 months because of the very slow rates of trends.

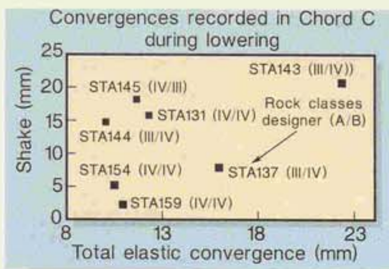


Fig 7. Irrelevance of rock classes in practice.

Referring to Fig 5 and the detail of the collapse, if we adapt the dispersion and corresponding period for trend definition from Fig 4 we should conclude that:

- just before collapse there was a deceptive deceleration to a five day period for definition;
- the faster immediate velocity of 0.7mm/day could require a two day period for trend confirmation. The rock and the shotcrete layer do not deform smoothly but by fits and starts, with micro-reversals of mini-trends to confuse the issue. That is why for 50 years wherever possible preference has been given to the monitoring of micro-acoustic generation.

Fig 6 summarises additional doubts regarding widely publicised behaviour models to be interpreted via displacement measurements. Note the difference (not unusual) in the long-term trends, and particularly the divergence. The geomechanical models do not include the differentiated behaviour possibly forced by the rigid shotcrete lining.

Geological classifications

The fundamental need for geological background information is indisputable. The point is, however, that in moving from

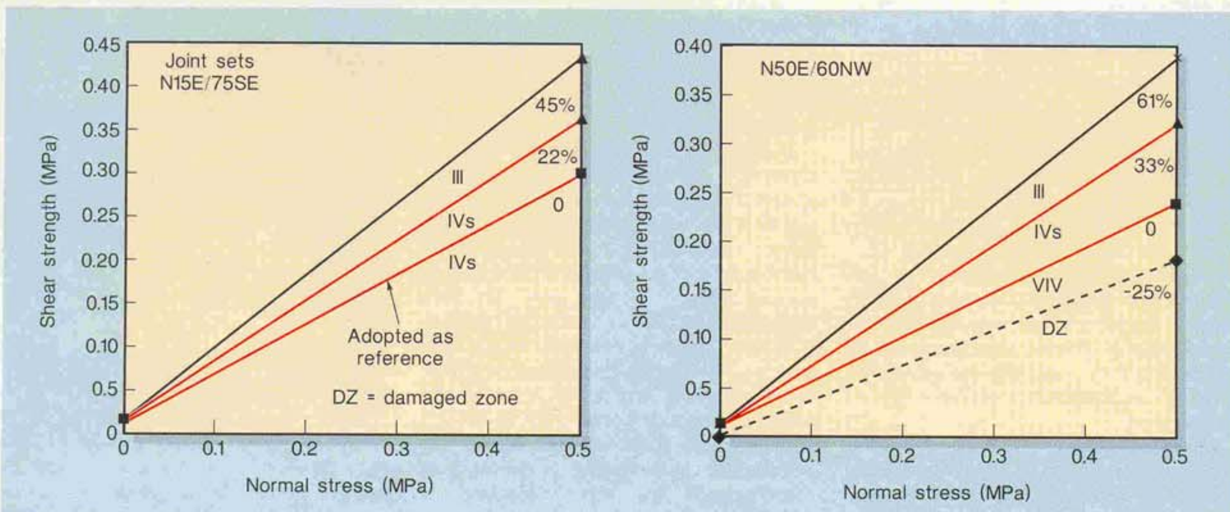


Fig 8. Shear strength equations which are attributed to joints.

the macro to the micro level of the significance of structural behaviour, overemphasis on geology as the single contributory factor has drawn attention away from the focus on real needs. Gross subdivisions into rock classes based on success/distress in executed tunnels have given rise to a belief which is not founded in fact, obscuring such crucial issues as the convergence/divergence behaviour of arches, the bearing capacity of arch-and-rib footings, the passive failure of arch base into temporary bench, and so on.

Meanwhile, the link with soil mechanics which still prevails (Terzaghi[4]) cannot be denied; here, different rock classes are transformed into equivalent roof support pressures. The dominance of shake has been shown in Fig 1, where the irrelevance of rock classes to the shake convergence becomes patently obvious (Fig 7).

Computational models

Consistent with the weight given to geology, the procedure of mapping the principal discontinuities was followed. Three well respected computer programs in current use were employed. Fig 8 shows the shear strength parameters adopted for two principal joint families. Note that only intrinsically soft materials can display such small variations from class to class. Small scale joints can well exhibit a zero strength (open joint, zero normal stress) and, at the other extreme, because of small rock-rock contacts or 'bridges', may well behave with high cohesion and friction.

In low stress ranges and under stress-release the effective ds/dσ friction can well be of the order of 70°. In a near-surface rock mass with open joints and joints weathered to clay it is assumed that normal stress on such joints may be zero over significant areas. Finally, as can easily be seen from the geometry, it is visionary to achieve arching in material separated by really parallel joints: desired behaviour relies on randomly occurring excrescences and angular dispersions around the nominal joint dips, plus consequent trapezoidal wedge actions, as the Romans discovered 2500 years ago when they developed the masonry arch.

In short, the analytic versions of schematic 'characteristic curves' and conventional computer model results of rock lining interaction tend to emanate from frauds on present-day rock mechanics.

Among the many questions thrown up by the case under discussion, I limit myself to one more gross fraud perpetrated on the rock mechanics currently in use. It is quite frequent, and understandable, that in facing acceptance of magnitudes of convergences, the reasoning is based on the insignificant proportion as compared with the tunnel diameter. Indeed, 50mm for a 15m tunnel seems unimportant — 0.33 per cent. However, there are three significant errors of concept here.

First, materials testing reports on percentage strains of the material and not on percentage displacements with reference to the cavity. Conventional errors thus start from the fact that geomechanical strains are very low in any case because the percent face displacement corresponds to an integration of much smaller micro-strains. Conventional rock (and soil) mechanics testing has rarely defined behaviours below one per cent strain, let alone around one per mille.

Finally, regarding equations of mobilised shear strengths, two grave omissions generally prevail: (a) the fact that in pre-peak behaviour at constant strains the cohesion component (in the linear equation) tends to be proportionally much greater than the friction one[3]; (b) the obligatory progressive failure assumption in rigid-brittle materials. ■

Part 2 of Victor de Mello's paper will appear in the September 1996 issue, together with his acknowledgements and a list of references. The paper was presented in the NAT '96 Conference, Washington, US, and aroused a good deal of interest. It is being reproduced here by kind permission of the publishers of the NAT '96 Proceedings, North American Tunnelling, A A Balkema, Rotterdam, the Netherlands.