Fallacies in NATM/RSST shotcrete supported tunnelling: Part 2

Continuing his paper from the July 1996 issue, Victor de Mello *discusses the computational models, analysis of convergence records and suggests a constructive approach in analysis and blasting control.*

Micro-strains prevail beyond a narrow collar of about 2-4m (or is it proportional to diameter?), as can be clearly seen in Fig 9. The Fig 9 results are beyond the scope of conventional Mohr-Coulomb peak strength equations of rock mechanics testing. A progressive failure condition is clearly suggested, even if constant parameters within the entire geomechanical mass were adopted.

One of the troubles with professional theorising on RSST it is often forgotten that the shotcrete layer should satisfy functions easily tackled in the structural engineering domain. It is common in civil engineering to check limiting hypotheses.

One assumes that the rock-concrete interface obliges the primary lining arch to work in unconfined compression.

A finite element program, ALGOR, was used to diagnose the effects of less uniform hypotheses and detect more critical tendencies for acceptable simplicity. Loadings were kept soft on the isolated shotcrete arch. Several runs were made. Results are:

- if overbreaks produce considerably varied cross sections, the limiting load to failure decreases considerably; in Fig 5D (*T+T*, July 1996, p39) decrease is to 50%;
- in exactly comparable analyses, drop in loading capacity is very marked if the feet of the arch are permitted to move instead of being fixed (rotation free); as the 'footing' modulus of elasticity was lowered to about 10 000kg/cm^2, the arch failed;
- a concentrated loading of 16 tonnes on an area of 20cm x 20cm (loose rock block) causes punching failure of the shotcrete;
- using ribs composed of rebar cages (total area of steel of 2.4cm^2) arch resistance increases only about five, 12 and 22 per cent for c. to c. spacings of 1.5m, 1m and 0.7m respectively, compared with the pure shotcrete arch prevailing if spacings are greater than 1.7m.

Analysis of convergence records

Because the tunnel design with progressive adjustments was based on convergence monitoring through conventional models, as prescribed in the RSST method, it was important to analyse the records more closely. Studies were based on monitored data of Chord C resulting from the delayed stage (lowering) of the tunnel.

Intuitively, the deformation was considered to be subdivided in three phases:

- initial: spurious, pertaining to 'installation effects', herein called 'shake', as logically, the immediately surrounding rock blocks react to the blasting vibrations;
- the second: presumed elastic;
- the third: elasto-plastic, evolving with time, either asymptotically decreasing or tending to slow failure, 'plastification'.

The dominance of convergences due to the shake component called for further analysis. First, the total of three partial bench lowerings was considered as one, and the distance was assumed to exert influence by an inverse square law: the resulting appearance was chaotic.

A point of apparent incompatibility must be emphasised, possibly calling for more early attention to crown settlements and convergences of Chords A and B. Having proved (via Chord C and reasoning only) that there are delayed effects, one reasons that at a given station x there should have been some accumulation of effects from earlier sections: x -1; x -2; etc.

The consistency of Chord C does not necessarily exclude as a first and anticipated reaction the crown accommodation by pressure increases and thereafter by settlements (duly overcoming the relative lining rigidity). The slight divergence (besides generalised near constancy) recorded in Chord C in many stations (*T+T* July 1996, p40, Fig 6A) just before excavation reaches the station may well be compatible with an ominous crown compression opening the legs of the arch before side pressures become dominant again.

Setting aside the dominant shake component, it is interesting to examine the presumed theoretical 'elastic component'. Because of the inevitable delayed setting of observation points, the presumed elastic convergences have to be extrapolated backwards. It was established from Chord C data that in most cases the 'total elastic convergence' might fit within the range of 1.3 to 3 times the actually monitored 'nominal elastic development.'

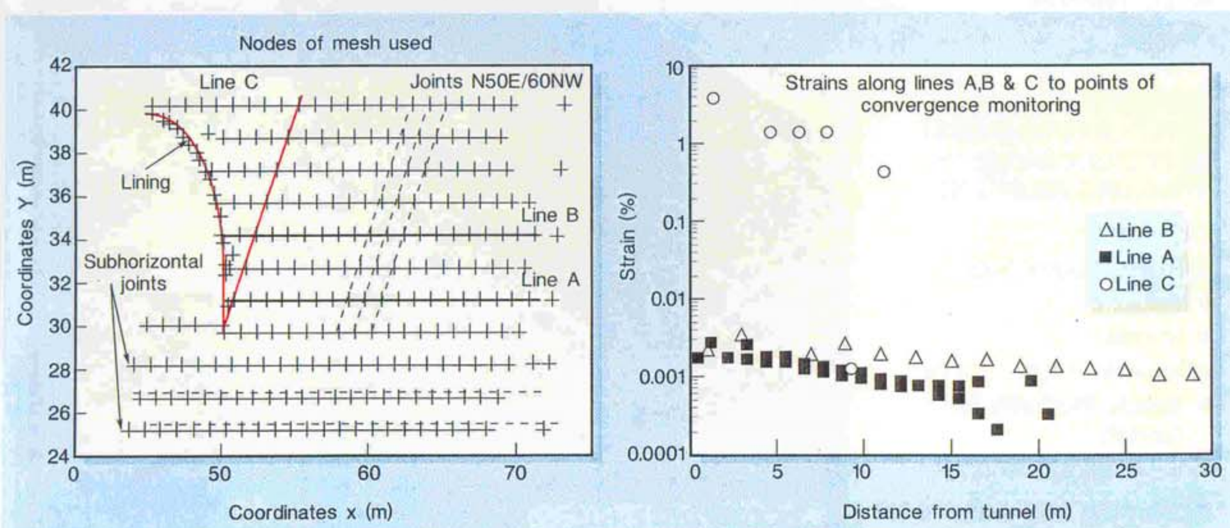
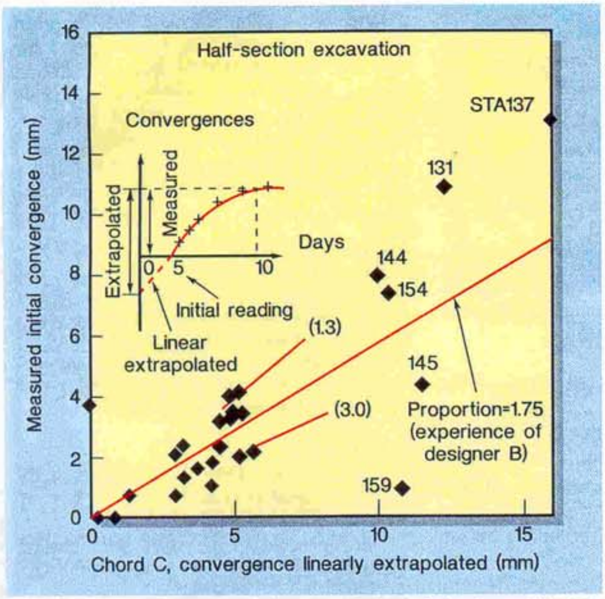


Fig 9. Examples of results interpreted from a typical current analysis by UDEC.



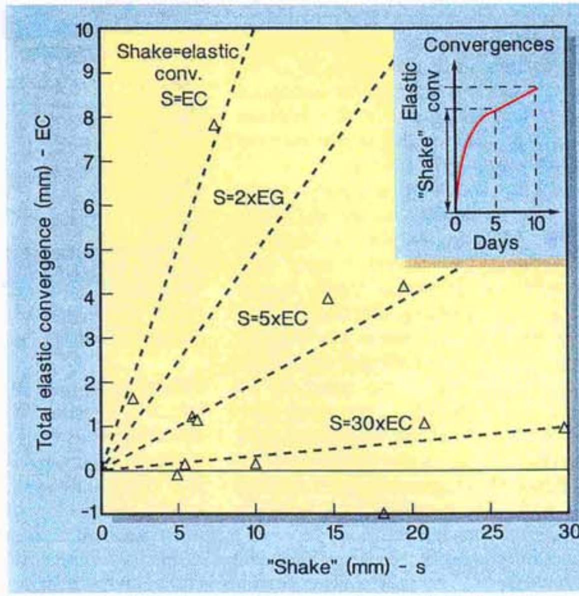


Fig 10 (left). Further analyses of presumed elastic behaviours. Fig 11 (right). Geomechanical relationship between shake and elastic convergence.

The search for rationality in convergence measurements (Chord C) as design indices continued. If a geomechanical behaviour was dominant, total convergence accumulated before the lowering excavation should bear some relationship to the nominal total elastic convergence due to the lowering itself: a wildly scattered plot resulted. Again, if the shake effect S had some dominant geomechanical component, some relationship should show up with respect to the total elastic convergence EC: Fig 11 proves that no such relationship existed — the shake S varied from one to 30 times the respective EC value.

Although the vastly dominant convergences followed no model, an attempt was made to correlate shake with intensity of face advances. The 'elastic' convergences of Chords C and F at the same dates were compared, after full excavation and primary lining had been achieved. As the ratio of Chords C/F increased, the wall lining of the upper half-section was more effectively mobilised.

Further, we analysed the convergence data of larger values in an undimensionalised manner. Seven stations gave reasonably similar trends. It was observed that the bands, including shake, showed a totally different pattern from the bands excluding the shake: the very perceptible attenuation with time is only apparent in the curves including shake, and not in the pseudo-theoretical curves excluding shake.

Finally, in order to check on the longer term nominally plasticising behaviours generally associated with linearity in log-time, the data from stations with larger measured convergences were plotted (Fig 10). Varied and varying behaviours were obtained. The observations are presumably significant, beyond the error band established: what shotcrete-rock interaction models are supposed to be signified?

There should be considerable room for reconsideration regarding the intensely publicised pseudo-theories that survive, principally because, in most routines, the final lining is constructed deliberately to be very robust and the temporary lining is not allowed to stand alone for long periods.

Careful analysis and control of blasting are important if blasting and accumulation of blasts provoke the dominant effect:

- it is fundamental to begin by conscientious optimisation of a blast pattern with due on-site monitoring of pilot rounds;
- sequential partial excavations might be much less favoured or accepted than appears current. Note that the partial section preference is not only associated with presumed face stability limitations but also

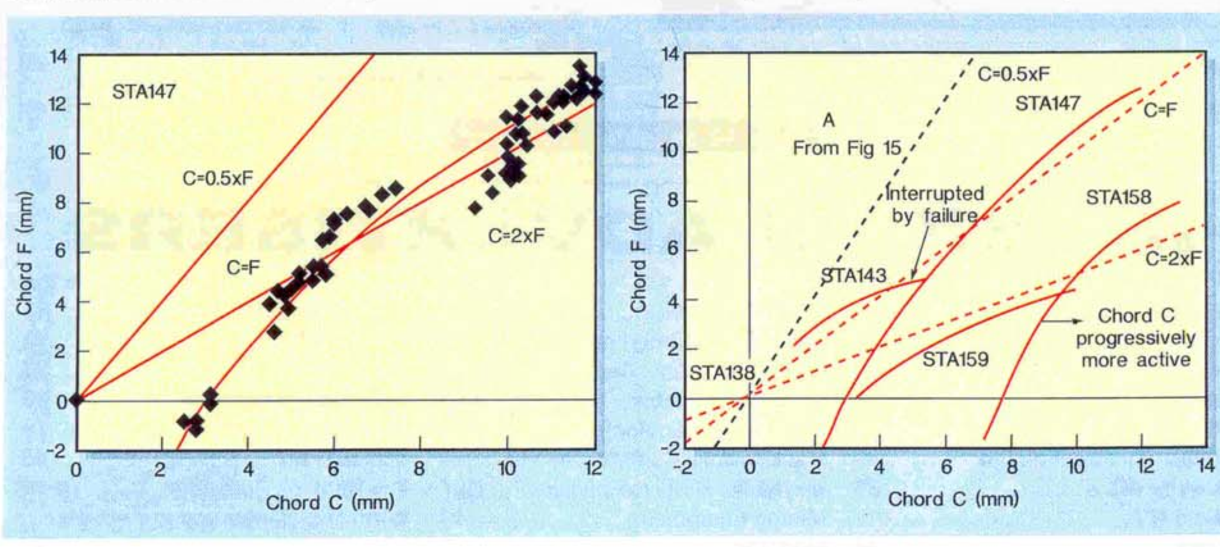


Fig 12. Shown above is an example of the comparative behaviour of chords C & F (elastic, same dates).

the contractor's logistics. Note also that damaging blast vibrations and limiting particle velocities and accelerations do not fit moderately into most frequent analogous data, principally because of the extreme proximity and the opening at which dynamic tensile stresses reflect back.

In practice, much more attention should be given to immediate rock bolting of the disturbed rock ring and also to the structural action of the shotcrete layer supported with ribs. It fundamentally important to develop in situ quality control, and not rely only on deformation monitoring.

The importance of time and the classic concepts of standup time need to be reiterated: the tendency to use more reinforcing treatments at the expense of time and the tremendous incentive for development of index tests, preferably on site and at face, to begin quantifying comparative standup time experiences.

Recalling the admonitions by Hoek, it is most important to add three other formidable problems not yet emphasised:

- the difficulty of evaluating the stress-strain-strength properties of the rock mass in medium dimensions under the dynamic conditions caused by blasting vibrations, and the somewhat pointless quest for an undisturbed in situ properties comparison with those of the rock 'as blasted';
- the difficulties of evaluating the static stress-strain-strength behaviour of the nearby rock mass after initial adulterations by the stress releases and micro-deformations coupled with vibrations;
- the frustration of dealing with progressive behaviours of cumulative micro-strains in an essentially rigid-brittle mass for which the deformation measurements transmitted through the rigidly set shotcrete layer are expected to provide the hint of when one might be approaching 'the last straw that breaks the camel's back'. More direct monitoring via micro-acoustic emissions and of increasing stresses, causative factors rather than displacements, remote effects, should be the way to proceed.

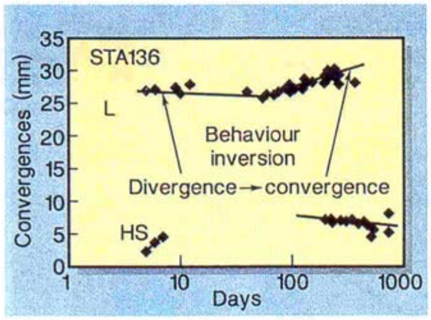


Fig 13. Convergence behaviour, interpreted as presumed elasto-plastic (t)5days).

Regarding the benefits of stand-up time, we might jokingly imagine that the important thing in RSST work is to move fast and loud enough to overcome the 'point of no return' of making oneself an acceptably experienced consultant. Thereafter, success becomes inevitable because one is always engaged on analysis in hindsight, which is easy, especially when confused logic joins hands with extreme dispersions to make predictions so fluid that moulding observations to wishful thinking is the simplest course and goes unobserved. ■

Acknowledgements

Deepest thanks are due to all bodies and persons involved, and especially to the owner and contractors who suffered the physical vicissitudes. Since the opinions voiced are strictly personal and still controversial, the author begs leave to maintain their anonimity until recognition becomes constructive and fully merited.

References

1. de Mello, V F B. 1966. With regard to in situ shear tests used in rock mechanics. *Proc. 3rd Bras. CSMFE, Vol I, VIII: 23041.*
2. Goodman, R E. 1995. Thirty-fifth Rankine Lecture: Block theory and its application. *Geotechnique. V.45 n.3:381-423.*
3. Hoek, E. 1995. Strength of rock and rock masses. The challenge of input data for rock engineering. *The News Journal of ISRM. V.2/2.*
4. Terzaghi, K. 1946. Theoretical soil mechanics. *John Wiley & Sons. 3rd edition.*

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