

LEADERS

Describe your education and career to date

Teenage experiments in constructing miniature earth dams for impounding water and creating artificial floods near our stone cottage in Wales led me to a BSc degree course in civil engineering at King's College, London, in 1963.

Guidance from my 'prof', Kevin Nash, then led me to a newly formed rock-slope research team at Imperial College, where my PhD student colleagues included John Sharp (director of GeoEngineering) and Peter Cundall, of subsequent UDEC and 3DEC numerical modelling fame. Perhaps Mr Cundall was stimulated by my inflexible, intersecting tension-fracture model studies of steep, excavated rock slopes using 40,000 miniature 'rock' blocks so that he soon created something more user-friendly for the profession.

Halfway through my PhD (1966-70), a memorable Thames-side lunch with Mr Nash's Danish colleague, Dr Laurits Bjerrum, director of the Norwegian Geotechnical Institute (NGI), eventually led me to Norway and employment in NGI's dam, rock and avalanche division.

The 25 years spent at NGI (1971-80 and 1984-2000) formed the primary influence in my professional career in rock mechanics and rock engineering. The first period involved both time and research budgets for developments in rock engineering and rock mechanics (Q-system, and rock and joint-strength criteria; the latter with the roughness parameter JRC). It was also the beginning of extensive national hydropower and foreign-project tunnelling work.

After four valuable years of research and in-situ testing at Terra Tek, Salt Lake City, my second period at NGI comprised five years of administrative and technical duties as division director. Reservoir engineering and rock mechanics laboratory groups were added to our previous dam and avalanche groupings, following the challenges of North Sea petroleum developments, including reservoir subsidence and borehole stability.

In my last ten years at NGI, I held project manager and technical advisor roles in numerous foreign projects, involving nuclear waste site characterisation (eg UK Nirex, SKB Stripa), hydropower project tunnels, caverns (eg Gjøvik) and dams, road tunnels, and bridge foundations (Hong Kong).

Since 2001, Nick Barton & Associates – a mostly one-man international consultancy – has bought me to many more challenging projects in a total of 35 countries. New experiences and travels occur every few weeks in a never-ending contact with the frequently unpredictable-in-detail hydrogeological environment found in numerous exotic project sites. These include double-curvature arch dams that exceed 300m in height, and railway tunnels (and TBMs)

Cue: Nick Barton

Nick Barton is an internationally acclaimed tunnel engineer, known for devising the Q-system of rock classification, who has researched and worked on a large number of tunnel projects worldwide. He talks to George Demetri

“Why select multiple-budget projects to save a few small percentage points on maintenance of escalators?”

stuck in lower Himalayan thrust belts. In 2000 and 2006, I wrote a book on TBM prognosis (QTBM) and also a cross-discipline text book on rock quality and seismic velocity.

Proving a source of pride, but also a significant challenge for 2011, has been my designation as the sixth Mueller Award lecturer at the next International Society for Rock Mechanics (ISRM) congress. This award honours the memory of our first ISRM president.

My chosen title will be: 'From empiricism, through theory, to problem solving in rock engineering'. Both in India and Hong Kong (frequently), and in China, this lecturer or short-course deliverer is introduced as "having a PhD from Empirical College", so the selected title of this lecture was self-evident.

You devised the Q-system of rock-mass characterisation in 1973-74. Describe how this came about and why it took so long for something like that to happen in the tunnelling sector

The Norwegian State Power Board (subsequently Statkraft) posed a request for a technical explanation as to why Norwegian hydropower caverns were displaying widely different magnitudes of deformation. This agency, which owns most of the world's electricity-generating capacity, was apparently not hurt by waiting more than six months for my report, which could not be written until a rock-mass classification method had been developed.

The nature of the question (chance or fate?) meant that rock-mass quality, rock-support needs (shotcrete) and rock-reinforcement needs

(bolts and anchors) for different sized openings, situated at widely different depths, needed to be linked to the different deformations recorded. This was a different and more challenging problem than addressed when Bieniawski developed RMR (rock mass rating) one year earlier – which I was not aware of.

The Q-value scale, and its six orders of magnitude, was gradually developed over six months of trial and error. The scale proved capable of answering the question posed, and has since proven to have simple links to rock mass, and joint and discontinuity shear strength, deformation modulus, seismic velocity and seismic attenuation, as well as tunnel and cavern-support needs, at depths from the surface to about 3km.

Why such a system (and Bieniawski's RMR from 1973) was not developed long before may perhaps relate to the increasing use of more economic single-shell solutions; these are epitomised the world over in our big caverns of 15-60m span. But, these solutions have been slow to achieve acceptance in our much smaller-section tunnels; notably those supported by the so-called NATM, where even the use of fibre-reinforced shotcrete has been slow to arrive in relation to its early use in Scandinavia.

How have approaches to tunnel support methods changed in recent years, if at all?

Chance or fate bought me to Norwegian 'nominally unlined' hydropower tunnel territory in 1971, which eventually amounted to more than 3,500km of such tunnels. Road and rail tunnels totalling some 1,500km have had the more conservative – but also single-shell – treatment of permanent support and reinforcement.

“Efficient pre-injection ensures project longevity and more predictable lifetime budgets”

“The ‘automatic’ application of deformation-enhancing steel sets almost always proves to be a false economy”

additional property of melting in a road-tunnel fire, thereby actually limiting damage. Spray-on sandwich membranes also represent an important addition to the tunneller's tool-box; each development responding to the various technical specifications required.

In contrast to the above, the cost and schedule of metro owners adopting the ‘short escalator syndrome’ tunnelling seen in some countries may cause just the top heading of the chosen NATM tunnels to average no better than 10m/week; it may also extend budgets and timeframes, causing settlement damage to hundreds or thousands of houses, even far from the tunnel, due to the apparent negligence of engineering geology principles.

Mixed-face construction can be avoided by also developing stations underground in rock, or at least in the best geology within reasonable reach. This, of course, means London clay in London. The best available tunnelling horizon need not include saprolite if the will is there to reach an ‘economic’ geologic horizon.

Escalator advertising makes a 45s stair journey at least as satisfying as 15s; this deeper approach may save years in construction time and hundreds of millions of dollars of taxpayers’ money, thereby accelerating city dwellers’ relief from traffic jams due to five-year budgets extending to new projects.

It is logical, and also a good investment, to save money and time when selecting better tunnelling conditions. Why select multiple-budget projects to save a few small percentage points on maintenance of escalators? Efficient pre-injection ensures project longevity and more predictable lifetime budgets.

Why do you think that some Himalayan TBM projects have not fared as well as they might have done?

I have seen tunnels brought to a standstill by lower Himalayan thrust belts, tunnel portals creeping down-slope, and tunnels contorted by their adverse siting within landslide areas. Each of these was due to less than ideal planning, and also limited site visits and investigations during the design phase. It is necessary to also evaluate whether the frequent or even dominant use of steel sets in such regions can be bettered. →



Contractor Robocon had already performed large-scale loading tests on S(fr), and the permeability of sprayed panels was already reported as 10-11m/s to 10-12m/s in the 1981 PhD of Oppsal. It was clearly time to start a support-recommendation update of the Q-system to incorporate S(fr) in place of S(mr). This non Q-design case-record collection was started in earnest by Grimstad of NGI in about 1987, and completed with our joint publication in 1993. Tunnelling case records numbering 1,250, and subsequent application around the world, represent a solid reason for taking NMT – the Norwegian Method of Tunnelling – as a serious alternative to NATM where conditions warrant the single-shell approach. Time and budgets also benefit.

Because the philosophy followed for over 50 years has been single-shell – with no possibility of reliance on concrete linings, except in special circumstances (such as a 4m sub-fjord tunnel closing due to swelling clay at Rafnes in 1973) – excellent developments of complementary tunnelling measures have followed during these past 20-25 years in Norway.

These included: a necessarily updated Q-system for selecting S(fr) thickness and bolt spacing; non-corroding PVC-sleeve double-grout annulus CT bolts (Ørsta Stål); a range of road-licensed diesel/electric trucks (AMV) for 15-25m³/h robotic S(fr) application (giving 4-6% rebound or better); and more recent use of

systematic (many kilometres) micro-cement and micro silica-assisted pre-injection, using 5-10MPa injection pressure, especially in some difficult road tunnels and our recent high-speed rail tunnels towards Oslo.

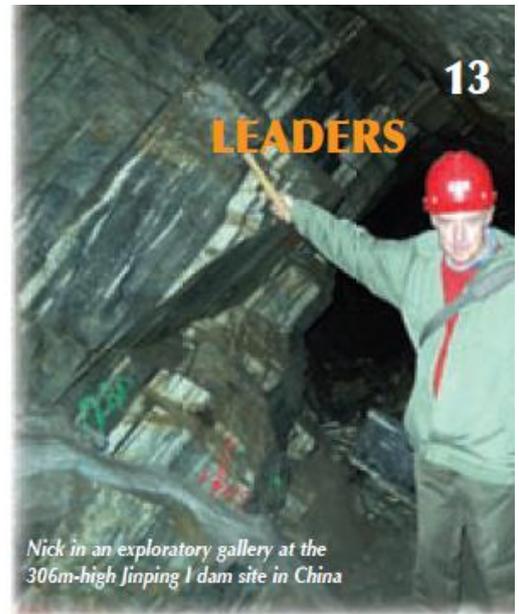
This process makes for surprise-free tunnels, driven at an average of 20-25m/week, which are complete at breakthrough (no benching, membrane or final lining). In effect, most Q-parameters have been improved by grout penetration. Prior support estimates (B+Sfr) appear to be greatly over-dimensioned if the benefits of pre-injection are not accounted for in final logging. Net savings are clearly possible, and time has already been reduced as delays are virtually removed.

Important international developments include the use of non-alkali accelerator so that S(fr) can be immediately built to the desired thickness. The excellent Dramix cold-drawn steel fibre, and the strong in-roads of polypropylene fibre such as Barchip, with its equally excellent S(fr) energy/deformation absorption, are also clear benefits to the industry. Polypropylene has the

The guiding philosophy of support class selection as you excavate is to: characterise the rock mass round by round, update prognoses, and use bolting and shotcrete of the best quality, and occasional concrete linings; or, leave it partially unlined in the case of headrace and deep-pressure tunnels to ensure faster and cheaper construction.

Of course, larger cross-sections are required to give the same water-pressure head loss in headrace and pressure tunnels. Maximum head reached 1,000m about 20 years ago where minimum rock stress justified this approach.

The first big change in my personal tunnel support experience occurred in about 1978 or '79 when first seeing steel fibre-reinforced shotcrete (S(fr)) used in a hydropower cavern under construction in western Norway. Lack of experience made my first reaction one of amazement and initial suspicion. On returning to Norway in 1984, no more mesh reinforced S(mr) was in use; only S(fr) and, of course, bolting. Steel sets were long since forgotten.



Nick in an exploratory gallery at the 306m-high Jinping I dam site in China

“Demanding owners do not realise that tunnel stability is constantly changing without appropriate support”

→ When arriving at tunnel faces in Norway with a mini-bus of foreign visitors, we far outnumber the two to three tunnel workers who are consistently busy at the face with drilling, bolting, shotcreting or pre-injection activities. These few tunnellers are well-paid, experienced and resourceful individuals. Cycle time for drill-and-blast advance is down to 5h in best conditions, and more than 160m in one week – even more than 170m has been achieved by Norwegian drill-and-blast contractors in separate projects in the last few years.

It seems that many Himalayan projects have a large number of less qualified and less experienced workers who frequently employ deformation-inducing steel sets. Cheap labour, cheap steel, and generally poorer alternative equipment, are compounded by the distinct and symptomatic lack of ‘additives’ in the shotcrete, concrete or grout, which might not be applied anyway until after the steel sets are installed to give the ‘correct profile’.

The ‘automatic’ application of deformation-enhancing steel sets almost always proves to be a false economy and can cost years in construction time. Less than systematic pre-grouting appears to be used for arch stabilisation, but not water control – also a false economy in most cases.

Can the mantra of ‘unforeseen geological consequences’ ever be a justification for the failure/delay/cost overrun of a project?

Returning to ‘short escalator syndrome’, referred to above, it is clear that shallow metro construction invites potential problems of cost and time overruns, due to factors ranging from rapidly changing tunnelling conditions and city-street hindrances preventing adequate pre-investigation. This includes boring and seismic characterisation due to the noise problem (sometimes even downhole). A new metro line cannot always follow city streets, which might otherwise make pre-investigation ‘easier’.

Take the case of the Line 4 Pinheiros station cavern collapse in São Paulo early in 2007. Even 11 cored holes in the station area, and five dedicated holes around and within the eastern platform cavern, failed to detect an 11m-high

ridge of rock. This, together with relic-joint structures in the overlying saprolite, may have loaded the temporary NATM support of lattice girders and 400mm of S(fr) with a ‘punching’ load as high as 15,000t due to an unusual non-arching situation, which was exacerbated by the opposing dips of sub-vertical foliation across the centre line of the 18m-deep cavern arch.

The unfortunate victims of this tragedy – pedestrians and four people in a minibus – did not only fall 9-10m on top of sand, soil and saprolite (a trauma they might have survived), but they were apparently drawn rapidly to their death by the suction effect of an air-blast. Firemen took 12 days to recover the bodies, mostly from the 30m-deep invert of the blocked running tunnel.

The unique combination of adverse circumstances, including a cracked stormwater drain ‘at the wrong location’ (crossing the major and planar discontinuity that marked the limit of the collapse directly under the road), added to this author’s choice of term – ‘unpredictable in the circumstances’.

The catalyst for this disaster was the central borehole giving the same depth-to-rock information as the other nearest boreholes, despite being drilled in the middle of an 11m-high ridge, due to the chance intersection with a deep depression in the ridge.

Of which areas of tunnel design do you feel we do not have adequate knowledge and therefore need further research?

Systematic pre-injection to control water ingress and improve stability is a process that is mostly poorly executed because pressure may be too low, the grout too coarse and additives not used sufficiently. Rejecting additives with a high unit cost is usually a false economy. When injecting at high pressure, several sets of joints may be penetrated, and 3D permeability testing before and after grouting has demonstrated rotation and reduction of permeability tensors.

At least the most easily penetrated set may no longer be ‘active’ after suitable treatment with stable, non-shrinking grouts, of which bentonite as an additive is not a valid candidate in today’s world with the availability of non-bleeding grout.

Further research is needed in estimating something that is rather difficult. What property improvement (higher velocity, lower deformability, less support needs) can we really document as a result of pre-injection? Can twin tunnel tubes be monitored using refraction seismic, permeability and deformation measurement – one with and one without pre-injection along a test section? An attempt will be made in Asia in the near future.

Are there any areas – whether to do with daily practice matters or design work – in which tunnel consultants could improve their effectiveness?

Those who like to perform numerical analysis, due to demanding owners who do not realise that tunnel stability is constantly changing without appropriate support, could benefit from daily visits to tunnel fronts to see the difficulties of the numerical representation of ‘every metre’.

A big cavern, of course, demands numerically assisted design. There is time to collect relevant data and perform modelling. But tunnels advancing 20-60m/week do not provide that luxury. The alternatives are clear: select the support class ‘as-you-go’ or ignore the variations and pay three times as much, with double instead of single-shell approaches.

What has been the most important lesson for you from your work as an expert witness (or as a participant on panels of experts)?

Keep cool and calm under pressure. Do not try to revenge those humiliated by aggressive lawyers – they are only doing their job, albeit perhaps too aggressively. Do not have more respect than necessary for those who may be misleading the proceedings with incorrect methods. In ‘panel of experts’ work, do not develop too much detail – it may be put in an appendix – and you might be considered ‘a threat’ in later stages of a project when ulterior motives may dominate over technical considerations.

What do you feel has been the greatest innovation in tunnelling in the past 40 years? Fibre-reinforced shotcrete and how to dimension it.

How often does your work give you sleepless nights?

Sleepless no, but maybe shorter sleeping hours when involved in something exciting. Anyway, three hours before breakfast is the best time to work.

“Keep cool and calm under pressure”