Rock mechanics applications in tunnel boring

William E. Bamford

University of Melbourne, Australia

Abstract

This paper is a subjective and non-technical personal commentary on the author's perceptions of the development and use of tunnel boring machines over the past few decades. It commences with a summary of some of the author's experiences and personal knowledge of some significant stages of the development of machine tunnelling, affected by geomechanical considerations.

It then continues with the author's generalized assessment of the groups of personnel working in the field of tunnel boring, and how their particular backgrounds training and interests interact to help or hinder the advancement of the art.

The paper concludes with recommendations to improve the effectiveness of rock mechanics applications to the design and utilization of tunnel boring machines.

1.1 A Personal History

It is now almost exactly 30 years since I first started getting interested in and involved with tunnel boring machines, and my working lifetime is almost as long as the modern development of tunnel boring machines (TBMs).

In 1957, when the Space Age dawned with Sputnik 1 going into orbit around the world, and some of the first TBMs built by Jim Robbins were in operation, I first worked in a tunnel, in the Tumut 1 tailrace tunnel in the Snowy Mountains Hydroelectric Scheme in Australia.

This tunnel had a diameter of 10 metres, and was being driven by conventional drill and blast techniques. My job was to record the geology of each face freshly exposed by blasting, and to estimate and record water inflow rates.

These tunnel mapping duties alternated with listening to rock noises in the Tumut 1 underground power station, which was being excavated in a highly stressed rock mass which was responding explosively to the excavation of a large hole in it by rock-bursting.

Geophones had been installed in boreholes drilled into the roof of the cavern, which was being excavated downwards from a top heading. This was before the days of computerized reading and recording of minor and major seismic events (rock noises and rock bursts). Rock noises were listened to through headphones, and the number of "clicks" heard per minute from each geophone was counted sequentially.

By daily plotting of the noise count at each site, any tendency for the noise rate to increase could be seen, and warning of impending rock bursts given when the trend line of rock noise rate versus steepened considerably.

My involvement with rock bursts continued and in 1970 I was asked to report on the explosive failure of a crown pillar in the Mount Charlotte underground gold mine at Kalgoorlie, Western Australia (felt in the town as a minor earthquake).

By analyzing the stress concentrations induced by the mining operations, and assuming that the pillar failure was in fact an *in-situ* strength test of a large volume of the rock

mass, I was able to advise the mine management as to mining strategies to minimize rockbursting during the extraction of the next, deeper, stoping block.
All these years later, rock bursts are still affecting the Mount Charlotte gold mine, and one of my Ph.D. students has just been seconded by the management of Kalgoorlie Consolidated Gold Mines to spend the next 2 years in field work there, implementing a seismic monitoring program and doing a considerably more sophisticated version of what I started there in 1970.

To return to tunnelling : During 1959 I worked in the Murrumbidgee-Eucumbene (Tantangara) tunnel, in 1959 and 1960 investigated the Snowy-Geehi tunnel and the underground alternate site for the Murray 1 power station (which was eventually built on the surface).

In 1960 I joined the staff of the Victorian Mines Department, and as part of a wide and varied range of applied geology work started the exploratory work for the Melbourne Underground Rail Loop. By 1964, exactly 30 years ago, the 2nd phase of this investigation work, *in-situ* measurement of soil and rock properties in test shafts and pilot tunnels, was commencing and the Victorian Railways Construction Board asked me to work full-time for them, in charge of the geotechnical investigations for the Melbourne Underground Rail Loop.

1.2 The Hydro-Electric Commission, Tasmania (*HEC*)

Through contacts with colleagues in Tasmania we became aware that the Hydroelectric Commission of Tasmania (the HEC) was considering the use of a TBM, for the first time in Australia. A young engineer named Griffiths, while returning from a holiday in Europe, visited the Oahe Dam site in South Dakota, and saw one of Jim Robbins' early machines in action. When he returned to Tasmania he wrote a memo suggesting that a TBM be considered for use in the Poatina Hydroelectric Scheme which about to be started. David Sugden was then working for the HEC as a mechanical engineer, and decided to do a cost/benefit analysis of the concept.

He had a shaft sunk into the Permian mudstones through which the tailrace tunnel was to be constructed.
He constructed a miniature TBM, 500mm in diameter, and tried boring the mudstones, both with drag bits and with 70mm disc cutters. He concluded that the measured advance rates of up to 90mm/minute were promising, and calculated that the cost/benefit ratio was about 1/4.
The HEC decided to seriously consider purchasing a TBM, and Ian Tulloch was sent on an overseas visit to inspect and assess all TBM manufacturers.
The HEC selected the Robbins Company, on the basis of their disc cutter experience, and
placed an order. David Sugden went to the Robbins factory in Seattle, where he took an active role (which he has continued to the present time) in suggesting modifications to the previous machine configuration and principles.
Innovations such as the floating gripper concept, used ever since, were directly attributable to his advice. He directed 3 phases of redesign and rebuilding of the machine when it was working in Tasmania.

At this time Jim Robbins, the founder of the Robbins Company, was killed in a plane crash. His young son Dick had just graduated from University with a Mining degree. He had not intended to go into the family business, but now suddenly found himself in charge of it. There were no orders visible, and he was starting the process of dismissing most of the work force and giving up the lease on the factory when the order from Tasmania came unexpectedly, "out of the blue".
Dick Robbins later said that he always had a soft spot for Australia, because that Tasmanian order saved the Robbins Company from folding up.
The history of TBMs may have been quite different had this occurred.

After successfully boring 7 km in the Poatina headrace and tailrace tunnels, the Robbins TBM was used by Tasmanian Railways to enlarge the Rhyndaston tunnel, on the line between Hobart and Launceston. In Melbourne we discussed purchasing the machine, as the Melbourne Silurian mudstones had comparable properties to the Permian mudstones in the Poatina tunnel. However the conservative, farmer-dominated government in power at the time was reluctant to be the first to introduce a new technique to the mainland of Australia, so the machine lay idle for some years, eventually being used in the Kangaroo Valley pumped storage scheme 200 km south of Sydney, N.S.W.

The government also ordered a slowdown in the progress of the Melbourne Underground Rail Loop project, so in 1967 I accepted an appointment to the staff of the University of Melbourne, as the first lecturer in rock mechanics to be appointed in Australia.
I am grateful for having been allowed to learn rock mechanics "on the job", by the Snowy Mountains Hydroelectric Authority, the Victorian Mines Department, and the Victorian Railways Construction Board. I learned the truth of the adage that "the best way to learn a subject is to teach it", and my experience in civil engineering works had to be supplemented by a new knowledge of mining rock mechanics, as I was mainly teaching Mining Engineering undergraduates and starting research work for Mining postgraduate students; later I also started course work for Civil Engineering postgraduates.

1.3 The Melbourne & Metropolitan Board of Works (*MMBW*)

In 1968 the Melbourne and Metropolitan Board of Works (MMBW) bought from the Robbins Company the first TBM to be used on the Australian mainland, and I started a long cooperative association with the MMBW (and its later successor, Melbourne Water).
Several of my students were able to conduct applied research on aspects of the first machine-bored tunnel, the 17 km long rock section of the 4.5 m diameter South-Eastern Trunk Sewer.

Interesting examples of the influence of geology on tunnelling conditions became apparent in the first months of tunnelling. The tunnel direction was about 50º oblique to the average direction of the fold axes in the moderately folded Melbourne Silurian mudstones. The report on the geological investigations for the project had been written by a geologist trained in general geology, rather than in engineering geology.
He made the apparently reasonable assumption that the quality of the fresh, unweathered rock mass would be higher than that of the weathered, partially decomposed rock mass. On that basis he predicted that tunnelling conditions would improve as the tunnel progressed away from the starting shaft position, moving under deeper cover, and consequently from highly weathered into less weathered rock.

The best tunnelling conditions (lowest support requirements, highest advance rates) could be expected when the tunnel progressed into fresh, unweathered rock.
The initial advance rates were better than had been expected, and the advance rates had been predicted to improve as the depth of cover above the tunnel increased and the rock got fresher. Several fold axes were traversed without serious incident.
Then the tunnel face moved into fresh rock and an anticlinal fold axis was reached. Surprisingly, progress halted.

Fold axes in bedded sedimentary rocks often have radial cracking and clayey bedding planes associated with them, especially in the vicinity of thin interbedded sandstones, which comprise about 30% of the Melbourne mudstones sequence.
The strata behave like a series of beams as they are being folded, with the outer fibre of each beam being in tension and the inner fibre being in tension.

If 2 beams are in intimate contact as they are being bent there will be differential movement between the 2 surfaces, and rock flour will be produced on the surfaces, easily chemically weathered into clay by exposure to groundwater.
The outer fibre tensile stresses can exceed the rock's (usually low or negligible) tensile strength, thereby generating a family of joints striking parallel to the strike of the fold axis and dipping towards the centre of curvature of the fold.
The radial tensile cracking tends to be far more prevalent in the thin, more brittle sandstone beds than in the more ductile mudstone beds.
The development of clay coatings or fillings on bedding planes tends to be especially marked on interfaces between sandstone beds and mudstone beds, where the contrast in stiffness over the contact between the 2 beds increases the amount of differential slip caused by the folding.

In the weathered zones of the rock mass the joints were cemented by limonite (hydrated iron oxides) and so, rather than being planes of weakness, they were in effect stronger than the rock substance.
In the fresh rock the joints were clean and open, and had virtually no strength.

The action of the rotating head of the TBM cutting into the anticlinal fold zone, was like undermining a dry masonry wall. The folded sandstone interbeds, usually only a few centimetres thick, were broken into "sugar cubes" by the folding-induced radial cracking. They were also usually associated with significant amounts of plastic clay, produced by the differential slip on the bedding planes.
The destabilizing efect of the TBM entering the axial zone of the fold was exacerbated by the fact that the machine had been designed and built as a hard-rock machine, with high cutter loads intended to bite into strong rock. These loads applied to the intensely jointed fold zone caused wholesale collapse of the "sugar cubes".
The mixture of "sugar cubes" and clay jammed in the muck buckets, prevented the rotation of the head, and stalled the TBM. Even if the TBM did manage to penetrate into the fold zone, the grippers could not get sufficient purchase on the walls to drive the machine forward at the required force levels, once the grippers were set into the clayey intensely jointed material.
Hand-mining techniques had to be used, to mine around and above the machine and stabilize the collapsing area, as well as to build foundations on the side walls for the gripper pads to push off, before the machine could proceed, after a delay of 2 weeks.
The first time that this occurred, following the initial several hundred metres of satisfactory progress, it was thought to be an aberration.
When the next anticlinal fold axis was reached, the previous pattern of collapse of the loose rock blocks mixed with plastic clay, jamming of the muck buckets, and stalling of the machine was repeated.

The true significance of the effect of weathering of the rock mass upon its stability was then realised by engineering geologist Warren Peck who was then consulted.

Instead of *Weathered Rock = Poor Tunnelling Conditions*, and
Fresh Rock = Good Tunnelling Conditions, the reverse was true.

It was also realised that the phenomenon whereby the TBM was stalled before it could be manually forced across each anticlinal fold axis was going to be repeated many times down the tunnel route.
David Sugden, who had left the HEC to become an expert consultant on design and modification of TBMs, was called in to assist MMBW staff (particularly Workshops and Plant Services Engineer Frank Watson) in solving the problem.
They devised the flexible slotted shield, which became known as "the Melbourne head" and became generally used world-wide during the following years.
The flexible slotted shield allowed spiles or forepoles to be driven above and ahead of the TBM, to support the loose ground. They also extensively redesigned the layout of the forward part of the machine, to ensure easy access to the face by personnel to apply support measures or to change cutters. Frank Watson had a full size mockup of the modified configuration made out of chipboard in his workshops,

so that the comfort and convenience of access by workers through the machine could be tested before it was rebuilt.

They also decided to replace the disc cutters by drag bits (to reduce the machine thrust forces required to achieve cutting) and to replace the muck buckets by an arrangement of radial arms with curved scrapers which pushed the muck straight onto the conveyor belt.

These innovations restored both the rate of progress and confidence in the future of the TBM. Confidence was gradually gained with the use of the forepoled spiles, and eventually they could control the movement of the intensely jointed fold zones sufficiently that the disc cutters were re-installed on the machine.

Eventually the skills of the tunnel engineers and machine drivers were so developed that the anticlinal fold zones were traversed with little trouble, and even with minimal use of the forepoles.

Research work carried out by staff and students of the University of Melbourne during the driving of the South-Eastern Trunk Sewer included the measurement of the *in-situ* rock stresses in the tunnel, measurement of the ground response of the jointed rock mass to the progress of the TBM, research into the mechanisms of cutting by the drag picks, and into the development of improved materials for drag picks.

1.4 The Melbourne Underground Rail Loop project (*MURL*)

By 1972 the decision to build the Melbourne Underground Rail Loop (MURL) had been made, and I was involved as rock mechanics advisor to the Principal Consultants for the project, the consortium of John Connell, Mott Hay & Anderson, Hatch, Jacobs. The MURL comprises 4 circular rail tunnels 7 metres in diameter, with its major part running through the same Melbourne Silurian mudstones as does the South-Eastern Trunk Sewer, and part of the MURL is approximately parallel to the route of the latter. The design team of which I was a member decided to stipulate that any tunnelling method adopted by a successful tenderer had to allow the placing of full circular ring sets within
1 metre of the tunnel face, and to allow the application of shotcrete up to and all over the face. The reasons for these stipulations were to prevent any possibility of uncontrolled ground collapses, considering that the MURL tunnels were to be the larger than the South-Eastern Trunk Sewer, and their position in the central business district of the City of Melbourne was considerably more sensitive to any surface disturbance.
No known TBM could meet these stipulations, and the team thought that tenderers would propose some configuration of road-header booms mounted on a multiple-deck jumbo, although we could not specify this, in the interests of preventing any claims by a contractor that we had forced him to use equipment which turned out to be unsatisfactory.
2 TBM manufacturers offered to supply machines which they said could meet the unprecedented stipulations of the Principal Consultants.
The successful tenderer for the tunnelling contract bought the machine which had been offered at two thirds of the cost of its competitor.
In practice, this machine appears to have been a conventional machine, of the type previously made by this company, but with a very much larger head imposed on it, with heavy ring erector gear 1 metre from the face, and shotcreting access arrangements.

After it entered service the contractor became concerned about the slow rate of advance that the TBM was achieving, and a claim was made against the "owners" of the project, the Melbourne Underground Rail Loop Authority (MURLA).
The contractor claimed, in effect, that the TBM was of a type that would give good service in normal rock, but that the rock in which it was being used was uniquely hard and/or highly tectonically stressed. The violence with which the rock failed against the face of the TBM was alleged to be the cause of the slow rate of progress. These claimed rock mass properties were not disclosed to the contractor, so this was a "Latent Conditions" claim.

David Sugden was asked to recommend modifications to the TBM, to enable it to cope with these unusual rock conditions. When the machine was opened up, in order to make these modifications, it was discovered that the main bearing appeared to be on the brink of failure.
A claim was made by the contractor upon his insurance policy covering the TBM.

The insurance company approached me for an expert opinion on the contractor's claims that the violence with which the rock failed against the face of the TBM was alleged to be the cause of the impending bearing failure, and also on the counter-claim by MURLA that the impending failure was due to defective design of the TBM.

I considered myself competent to comment upon the rock strength and stress properties, but asked a colleague in our Mechanical Engineering Department, Dr. Andrew Samuel, to analyse the machine design. He had previously consulted on failures of large bearings in such situations as cement kilns, so felt competent to tackle this problem.
After extensive analyses he demonstrated the deficiencies of the bearing for the loads which were unavoidably imposed upon it by the TBM size shape and configuration.

David Sugden was then commissioned to make an extensive redesign of the TBM, to render it usable. Apart from totally redesigning the main bearing mountings and seals, he made many other innovative changes. The head had to be much thinner than any previously constructed, being over 7 metres in diameter but less than 1 metre thick, to allow for the support placement stipulation to be met.
He designed a full circle stressed-skin head, with multiple side discharge buckets.

The original machine had only 4 large buckets, which dumped their loads from the top of the tunnel down onto the centrally located conveyor belt, flooded it, and caused excess muck to spill over the machine. David Sugden replaced this situation with 12 smaller muck buckets, discharging onto a side conveyor - the first and only time a side conveyor was ever used on a TBM.

The heavy cumbersome support erector arm was replaced with an ingenious system of pulleys and slings around the side of the machine. As David Sugden has said, "just the sort of thing that a boy from the bush would think of!"
Apparently the tunnel crew responded enthusiastically to the intellectual challenge of mastering the complex arrangements, and eventually achieved excellent productivity.
2 of the propel rams were redundant for the redesigned machine, and were removed.
Much time had been wasted by the support placement crew in cleaning the muck off the floor of the tunnel so that they could insert the invert component of each ring set.
The 2 surplus propel rams were put to good use, acting as shock absorbers to drive a plough just behind the machine head along the invert of the tunnel to clean it, so that rings could be placed in the invert without having to dig it clean.

The extensive redesigns and reconstruction of the TBMs on these 2 projects can be viewed as good illustrations of the interaction between geomechanics and machine design.
In the first case, unappreciated geotechnical facts caused the machine to fail to perform, so it was ingeniously redesigned to cope with the geotechnical facts.
In the second case, stipulations were placed on machine configuration to enable it to cope with geotechnical conditions, but the machine was not in fact adequately designed, until after it had failed.

1.5 The Thomson-Yarra Tunnel

In 1962 it was evident that if the population of the Melbourne metropolitan area grew at the rate being projected, the catchment areas would be inadequate to supply sufficient water for the projected needs of the industry and population of the greater Melbourne area within 10 years. The catchment areas were mostly on the headwaters of the Yarra River, which flows through the centre of the City of Melbourne, and some of its tributaries.

These rivers drain south from the mountains of the Great Dividing Range into the Southern Ocean via Port Phillip Bay. The apparently logical source of an augmented water supply was the Big River, which drains north from the Great Dividing Range into country Victoria and eventually via the Goulburn and Murray Rivers into the Southern Ocean near Adelaide, South Australia. The Big River's catchment was contiguous to the catchment of the Upper Yarra River, and rain falling on opposite shoulders of the Warburton-Woods Point Road, which runs along the crest of the range, may end up flowing south into the Yarra River or north into the Big River.

A north-south tunnel about 10 km long through the Great Dividing Range would have enabled the diversion of part of the flow of the Big River, to ensure the adequacy of Melbourne's water supply until the end of the century.

However, the Big River is one of 4 major rivers which feed the Eildon Reservoir, which was built in 1952-55 to ensure a steady flow of water to the irrigated farms and orchards of the Goulburn. The farmers mounted an emotive political campaign to prevent any of "their" water from being diverted for the use of the "greedy unproductive parasites" living in the big city. The conservative farmer Premier of the day responded to this campaign, and vowed that "not one drop of water will ever cross the Divide!"

The MMBW was directed to divert water instead from the Thomson River, via an east-west tunnel 37 km long. The Thomson River is a tributary of the La Trobe River, flowing eastwards through the La Trobe Valley, through the Gippsland Lakes and into the sea in Bass Strait. The La Trobe Valley is an industrial region in which most of Victoria's electricity is generated in brown coal-fired power stations. It elects mostly socialist politicians, so it was a logical action for the conservative Premier to choose to offend the supporters of the opposition party, rather than his own.

It was decided that the new, much longer tunnel should be driven in 3 stages.
The time expected to be necessary to investigate a new alignment (after several years had been spent in investigating the Big River diversion) and then to drive the long tunnel
(about 32 km in a straight line) would have left Melbourne short of water, and subjected to water rationing each summer, before it could be expected to be completed.
The 3.7 m diameter Stage 1 tunnel, 20 km long, was driven between 1969 and 1975 to intercept the upper headwaters of the Thomson River, in time to augment Melbourne's water supply, hopefully before the annually increasing demand could outstrip the total supply. The Stage 2 tunnel, 10.7 km long, intercepted the Jordan River, a tributary of the Thomson River, in 1978.
The Stage 3 tunnel, 6.4 km long, leads from an intake on the shore of Lake Thomson, which was formed by the construction, commencing in 1978, of an earth and rock fill dam 165 m high. The Stage 3 tunnel was bored between 1979 and 1981.

The Stage 1 and Stage 2 river diversions were both well above tunnel level, so involved building diversion weirs and drop shafts to take the water down into the tunnel.

The entire tunnel route lay beneath unoccupied country, having reverted to a state of almost virgin wilderness since its exploration by gold prospectors a century ago.
There were few public roads or access tracks, apart from some forestry fire trails.
The geological investigations for the Stage 1 tunnel were entrusted to a brilliant paleontologist, with experience in regional geological mapping, but not in geotechnical work. Selection of each site for exploratory diamond drilling seems to have been influenced by the ease with which bulldozer drivers could prepare a platform large enough for the drill rig to operate from, by excavating a side cut into a steep hillside.
The rock sequence is a series of steeply-dipping alternating sandstone and mudstone beds. Sandstone outcrops were too hard for the bulldozer to be able to cut satisfactory drill sites in them, so almost every drill hole was collared in mudstone, and

because of the steep dip of the bedding could remain in the same bed for a long distance.
Inspection of the cores would give an erroneous impression of the amount of sandstone likely to be encountered.
Expert consultants such as David Sugden warned that the sandstones would be probably present difficulties to a TBM, but the contractor, a joint venture of 2 firms, one Australian and one American, decided to buy a Robbins TBM.
The project manager estimated the predicted production rate as about 2 metres per hour, but in the first 400 hours of operation the average penetration rate was 1.3 metres/hour, and only 0.75 metres/hour in the hard sandstones.

This slow rate of progress and high cutter consumption rate led to the decision by the joint venture to overrule the project manager, and change the tunnelling method from TBM to drill and blast.
The TBM was allowed to continue operating while the necessary tunnel drilling equipment was acquired. Ironically, the rate of progress of the TBM improved after the termination decision was made, probably because of increasing experience of the operators and the fitting of superior quality cutters, and in its final weeks of operation its penetration rate was up to the target rate.

It is interesting to compare the fate of the TBM on the South-Eastern Trunk Sewer with that on Stage 1 of the Thomson-Yarra Tunnel.
In the former case, the TBM was owned by the project "clients", who persevered and innovated and used the resources of other parts of their organisation to modify and improve the TBM until it performed satisfactorily.
In the latter case, the joint venture of 2 private contractors apparently had no "surplus" resources, and did not persevere with the machine when it appeared that, if the advance rate did not improve, the contract could not be completed by the target date.

A hasty decision was made that the machine was inadequate, and should be discarded.

After this experience it is not surprising that Stage 2 of the Thomson-Yarra Tunnel was driven by the drill & blast technique.

When Stage 3 was commenced in 1979 a TBM was chosen.
Part of the reason for this was to use it as a trial of machine boring in very strong rock, for the probable next tunnel in Melbourne, the Western Trunk Sewer.
This tunnel was to be excavated through hard strong basalts, as strong as any rocks which had ever previously been machine bored, but free from quartz.
The Stage 3 tunnel runs through a sequence of Ordovician mudstones, having unconfined compressive strengths of up to 300 MPa. The Robbins TBM supplied was designed to be deliberately "overpowered", with available thrust of up to 40 tonnes/cutter. This was to ensure that the desired penetration per revolution of the head could be maintained. The machine performed well, seldom needing to use all the available power.
There was a suggestion that the machine might actually be used to excavate the Western Trunk Sewer. Upon the successful completion of Stage 3 of the Thomson-Yarra Tunnel the TBM was taken to western Melbourne suburb of Sunshine, to excavate the Anderson Road Main Drain through basalt.

This proved that applying high thrusts to large diameter disc cutters was an effective way to cut hard rock.
One problem found with using large and heavy disc cutters though was the difficulty of changing cutters on this type of TBM. Worn cutters had to be manhandled down off the face of the machine, through a muck bucket and along the conveyor belt, through the head of the machine. Fresh cutters had to be manhandled back the same way in reverse.

1.6 The Western Trunk Sewer

The investigations through the late 1970s showed that the basalt plains lying just to the west of Melbourne were not homogeneous. The Newer Volcanics had been laid down by several discrete lava flows. Sufficient time elapsed between successive eruptions for soil profiles to be developed in the upper part of each flow, and sediment-filled stream valleys to be cut into them, before being filled and covered by the next flow.

This meant that the basalts, although hard and strong, had water-logged subhorizontal soil layers through them.

The MMBW stipulated that the TBM had to be a hard rock machine, able to cope with sudden large sustained inrushes of water, and to be able to cope with situations when the gripper pads on the side walls would be bearing on soft clays.
The previously-used situation of having cutters changed by workers working in a narrow unsupported gap between the head of the TBM and the face of the tunnel would expose them to danger from possible water inflows. So, it was also stipulated that it be possible to change cutters from inside the head of the TBM.
The resourceful designers of the Robbins Company, particularly the ingenious John Turner, responded to the challenge by designing a double-shielded hard rock TBM, which could use either conventional gripper pads when the side walls were rock, or use the entire circular rear shield as a gripper in soft ground.
A novel triangular configuration of steering rams was used here for the first time, as was the system of double wedge locking of the disc cutter mountings, which enabled them to be drawn back inside the head of the machine.
The concept of using large, highly loaded disc cutters to cut hard rock was again proved to be effective, and triggered David Sugden's concept for the "Mobile Miner".

The experience of more than 20 years' cooperation between the MMBW and the Robbins Company indicates to this outside observer the value of having a long-term and far-sighted relationship of mutual respect between an informed client/user and a competent and innovative manufacturer. The MMBW was prepared to persevere when difficulties arose, and help the manufacturer to come up with a mutually acceptable solution, rather than resort to litigation and dispute resolution to solve the problem financially rather than technically. Also, having the advice of an expert, highly experienced consultant like David Sugden, not on the TBM manufacturer's payroll, allowed him time and space for reflection, and therefore enhanced his creativity.

1.7 The Mobile Miner

By the early 1980s David Sugden realized that the extrapolation of the concept that greater effectiveness of cutting by disc cutters could be ensured by having larger cutters would indicate that greatest effectiveness could result from having a few very large disc cutters traversing the face of a tunnel. The use of very large disc cutters, each loaded by sufficient thrust to ensure their penetration to the optimum depth, would require very large propel forces, and therefore very large gripper ram loads, if many cutters were used. Instead of applying 30 tonnes thrust to each of 20 to 30 "small" (i.e. 38 cm diameter) disc cutters simultaneously, the same total thrust applied to one or a few very large cutting discs might enable very strong rock to be effectively and rapidly cut.
By having the disc cutters mounted on a cutting wheel which rotates about a horizontal axis at 60^o to 90^o to the tunnel axis (rather rotating about an axis parallel to the tunnel axis) it would be possible to cut non-circular openings with flat floors, which would be more useful to the mining industry than circular tunnels.

This concept was put to the test with the design and construction of the first Mobile Miner in 1985, its trial in Seattle and then its use in the Mount Isa Mine, Australia.

Its performance there led to various design improvements for the second Mobile Miner which was commissioned by NBHC (now Pasminco) in 1989 for trial in its mine at Broken Hill, Australia.
A third, still-more-improved version of the Mobile Miner has recently been built for the Taisei Corporation of Japan.

Some very interesting advances in mechanical analysis and design techniques have been made on this project, as have computerised monitoring, control and feedback techniques for automatic operation of the machine, which will be necessary to effectively use a machine which is too complex for any human to be able to control in real time.

From the rock mechanics viewpoint, findings of interest have been :
1. the confirmation of the great influence of joint spacing and orientation upon machine penetration rate;
2. the realization that it is not possible to extrapolate a TBM performance prediction model developed for "conventional" machines and cutters (i.e. the N.T.H. Trondheim model) to an "unconventional" machine like the Mobile Miner.

1.8 How to design TBMs

As was mentioned in Section 1.4 above, during 1977 Dr. Andrew Samuel and I collaborated on a report as to the causes of the main bearing failure on the MURL TBM. After I had demonstrated for him all the rock mechanics test procedures which I carried out for the MURL project he asked the provocative question "How do the machine designers go from your numbers to model the flow of forces through the TBM, and thereby actually design the machine?"
After some reflection I had to confess that as far as I knew, there was no such logical use made of my painstakingly obtained and measured rock properties.
The rock test values were used as indices of how much stronger or weaker, more or less abrasive, the samples from a new project were than had been the rock on some previous project for which TBM experience had been obtained.
As a teacher of mechanical design, Andrew Samuel commented that it all seemed rather "unscientific" and *ad hoc*. I had to agree.

We agreed to work together to try to investigate the links between rock mechanical properties and machine forces, and consequently to try to formulate some improved design procedures for TBMs.
We built disc cutter force transducers, which were installed on the TBMs boring the Stage 3 Thomson-Yarra Tunnel, Anderson Road Main Drain, and Western Trunk Sewer, and tried various techniques for monitoring and recording these forces in real time, while cutting was proceeding.
F-M Telemetry was tried in the Thomson-Yarra Tunnel, with hard-wired connections from the disc cutters to transmitters mounted in protective boxes in muck buckets, which sent coded FM radio signals to a receiver and recorder in the driver's cabin.
The presence of several hundred tonnes of TBM metal in the tunnel, on the path of the radio signals, caused unacceptable distortion and degradation of the signals.
In the Anderson Road Main Drain we used hard wired connections from the disc cutters to the computer which recorded the data. By manually rotating the wires 24 times in the direction opposite to that of the TBM head rotation before the connections to the recorder were soldered and the TBM was started, we were able to take continuous force readings through 48 revolutions of the head, before the TBM was stopped to allow us to cut the connections.

On the Western Trunk Sewer we were allowed by the MMBW to install a series of slip-ring connectors in the hub of the head while the TBM was being built at the Bendigo Ordnance Factory in rural Victoria. These allowed the instrumented disc cutters to be installed on the head, and continuous force readings to be made at any desired time throughout their life, until they were replaced. Many readings were taken of the actual thrust, rolling, and side forces imposed on the disc cutters while cutting rocks of various strengths and quality.

Notwithstanding the best efforts of postgraduate research students L. P. Seow, Alex Duran, and Juan Jofre and ourselves, it does not seem that our original goal, of eventually being able to control and "fine-tune" a TBM's performance by monitoring actual cutter forces in "real time" is likely to be soon practicable.

At about the same time as we started this research work, David Sugden started developing a set of mathematical models to predict TBM performance.

Semi-empirical rock boreability factors were derived, based initially upon experience and intuition, then refined project by project in the light of actual versus predicted performance. These were incorporated into a series of equations which modelled the machine advance rate in terms of the geometry, power, and other operating variables, and which were in their turn refined in the light of experience. This subtle and complex method, combining some aspects of rock mechanics with many aspects of machine design theory, and refining its assumptions and weighting factors with each new quantum of experience, exemplifies the "*Consultant's*" approach which will be discussed below.

2.1 Players in the Rock Mechanics : TBM collaboration.

I wish to discuss some of the problems and challenges in terms of 3 different groups of workers and professionals involved with TBMs.
As a simplification, I will term them "***Academics***", "***Consultants***", and "***Builders***".
I will speak deliberately simplistically and provocatively, in order to illuminate these problems and challenges, and also perhaps to point towards some conclusions.

Many people, including this author, may work under more than one of the labels, or have personalities and attributes of more than one.

The main problem, as I perceive it, is a gap or hiatus between what the rock mechanics "Academics" do, say, or measure and what the "Builders" do. (The term "Builders" is intended to cover both the TBM manufacturers and the tunnel contractors.) The "Consultants" often mediate between the "Academics" and the "Builders".

2.2 "Academics"

Academics may be University professors or postgraduate students, or may be research scientists or engineers working for government research institutes.
A few of them are specialists employed by *Builders*.
Academics work by applying the model of the scientific method, to attempt to rigorously and reproducibly derive some universal truth or law from objectively measured data.

Some *Academic* rock mechanics practitioners tend to write case histories correlating the performance : advance rate (instantaneous or per shift) and cutter consumption with rock properties and/or laboratory cuttability indices. On the basis of these back-analyses or retrospective calculations, predictor equations can be written.

There is a tendency for academics to demonstrate their originality or independence of thought by choosing novel combinations of "independent variables", so as to avoid the charge of plagiarism of other authors' initiatives.

When a new TBM project is being planned these or similar academics may be given samples of exploratory drill core to perform tests on and provide what they or the consultant design engineers think are the relevant numbers from which the viability of using a TBM may be assessed, and its probable advance rate and cutter costs.

They may be asked to extrapolate their predictor model derived from the data from a particular machine, to make predictions about the tunnelling costs and performance of an as-yet undesigned machine.

Other *Academic* rock mechanics practitioners, with more "hands-on" experimental leanings, and access to substantial funding, set up tests of cutting mechanisms in laboratory conditions. In Universities these tests tend to be limited to using reduced scale models of the cutting tools and/or cutting simulated rock or very uniform blocks of quarried dimension stone. Other researchers in industry-funded laboratories have been able to conduct their tests with full-size tools.

Useful insights as to the mechanisms of cutting have come from such experimental work, and equations which can be used in the *Builders*' predictive techniques have been derived.
The application of the results of laboratory cutting tests to prediction of TBM performance is hindered by the necessity to express the measured laboratory cutting forces and cutting performance as functions of *(a)* cutting tools geometry and configurations; and *(b)* the mechanical properties of the rock being cut.
The different values of *(a)* for the real TBM situation can be adjusted for, but in many cases the field values of *(b)* are only reliably known after the tunnel has been driven.

New young rock mechanics practitioners are generally trained in the "scientific method" approach. This follows the fictitious pattern allegedly involved in their writing of a doctoral thesis. According to this hopeful fiction a candidate critically reads all the relevant literature, sees where a previously unsolved problem exists, plans an experimental program to solve the program, conducts the program with an objective unbiassed and open mind, analyses the experimental results, draws out the valid conclusions, verifies them with statistical and factorial analyses, discusses the implications of the findings, writes a triumphant conclusion, and makes suggestions for future work.
Having been rigorously trained at an early and impressionable stage in his career that this slow deliberate "scientific" method is the only respectable one, it may be difficult to later break this manner of working.
Another part of University research training is to value published papers above all else. Every thesis or research report must be published as soon as possible, in as many instalments as it can decently be subdivided into, if an *Academic*'s chances of getting tenure or promotion or research grant funding are to be maximised.

This necessity to publicize, in order to impress peers and superiors, is in conflict with the desire of *Consultants* and *Builders* to preserve commercial confidentiality.

2.3 "Consultants"

Consultants are mostly employed by specialist geotechnical consulting firms.
Some work for *Builders*.
A few of them are University staff, attempting uncomfortably to wear 2 hats at once.

Consultants work by drawing on their extensive experience and self-confidence to rapidly and assertively give clear and unambiguous recommendations to their clients, based on a volume of data which the *Academic* would regard as insignificant, and at a speed which the *Academic* would regard as impossibly fast.

The expert *Consultant* is required by his industrial clients the *Builders* to demonstrate qualities and work patterns quite different from those of the *Academic* to be successful.
He has to be decisive, giving quick and possibly subjective decisions or recommendations based on the confidence gained from decades of experience.
He is usually not afforded the time to follow the "scientific method" and make a long rigorous investigation to produce a report hedged with qualifications, which reads like a publishable research paper. He needs to write concise unambiguous reports, with no expectation that they will be published.

Consultants are unashamedly subjective, in contrast to the determinedly objective *Academics*.

2.4 "Builders"

Builders include both the designers and manufacturers of TBMs, and the contractors who use them to construct tunnels.
Many of them believe in the old adage "If it ain't broke, don't fix it!"

The manufacturers of TBMs take little notice of *Academics* other than the ones on their own payrolls, whom they may have trained to do their own translations into *Builder*-talk.

Contractors and constructors have learned to communicate with *Consultants*, or rather the *Consultants* have learned to communicate with the *Builders*, if they have survived in business.
Contractors and constructors take little notice of *Academics*, except to use them to refute or confuse expert evidence given by other *Academics* to or on behalf of *Consultants* working for the "Owners" of their projects.

The machine manufacturers do not use the Academics' predictor equations to design their TBMs. They probably do not even use many of the strength and cuttability indices enthusiastically measured and reported by the Academics; if they do, they probably put the *Academics*' reports through a translation process to convert them into a useable form, and modify the reported rock properties with secret or proprietary weighting factors, based on their own experience.
Sometimes they totally ignore them.

They may have "secret" design equations or procedures to design their actual TBMs, using these secretly transformed rock substance and rock mass properties and a series of assumed geometries. For such a machine figures will be calculated (derived from the confidential data bank of past experience) of probable advance and cutter wear rates,costs, power consumption, torque on main bearings, etc.
By rerunning the computer model with other machine geometries (e.g. cutter sizes number and spacings, penetration per revolution, shape, revolutions per minute, etc.) new performances can be calculated, until an optimum is reached.
This will be the machine offered to the client, and its performance may vary greatly from that predicted by an Academic from his type of predictor model.

If the manufacturer sells the TBM, any discrepancies between its predicted and actual performances may be used to modify the weighting factors or calculation steps, or even to suggest new steps for the estimation procedure.
Not only do the size and reliability of the TBM manufacturer's data bank increase with each new project, but the effects of any improvements in machine design and technology can be estimated, and factored into the prediction procedure before the improved machine is marketed.

This model of the competent TBM manufacturers' procedures has not necessarily been followed by the less competent manufacturers. They may merely offer a new client a copy of the last reasonably successful machine that they sold, hopefully but not necessarily one which operated in a rock with vaguely comparable strength in the past.

3. Towards the Future.

I feel that more progress could have been in the improvement of TBM performance and predictive methods during the last 2 decades, if there had been more cooperation between the groups of workers broadly described above.

The atmosphere of fierce commercial competitiveness and secrecy among the rival *Builders* has resulted in under-utilisation of the intellectual energy and talent that was available among the *Academics*. While understanding the attitude that "knowledge is money" and that disclosing trade secrets could prevent a *Builder* from reaping the full financial benefits of his innovation and investments, I believe that it is arguable that more of a spirit of like-minded cooperation among experts working towards improvement of TBM practice could have made money for all participants.

In essence, I believe that there has been competition for a bigger slice of the cake, rather than collaboration to increase the size of the cake.

A wasteful situation has existed where initially enthusiastic and well-meaning *Academics* have attempted to conduct research into applications of rock mechanics to TBMs, without knowing or being able to find out exactly what the industry felt it wanted from them.
The *Builders* may have been suspicious of the motives of the *Academics* , with the "Publish or Perish" syndrome appearing to drive them, and unable to comprehend that many *Academics* can be genuinely disinterested, and not driven by desire for commercial gains.
It seems unfair for *Builders* and *Consultants* to deride *Academics* for being theoretical and impractical, while being unwilling to disclose to them just what it that they want to have measured and analysed.

There are some promising developments in applied research, as pointers to the future. For example, in Australia, the Centre for Mining Technology and Equipment in Brisbane has recently begun a program of research into mechanised excavation, involving cooperation between the Australian Mineral Industry Research Association (AMIRA), the CSIRO Division of Exploration and Mining, the Robbins Company, and the University of Queensland, funded also by the Australian Government through their Cooperative Research Centres (CRCs) scheme. It is to be hoped and expected that this scale of cooperative effort will lead to substantial advances, which will be disseminated for the benefit of the industry.

Finally, there remains a challenge for the *Builders* and *Consultants* to cooperate with the *Academics* in helping the latter to train intelligent and practical recruits for the former.
It seems likely that there will be a steady increase of mechanized excavation and also in the numbers of University graduates in the next decades. The best and the brightest will not undertake specialist training to fit them for productive work with the *Builders* and *Consultants* unless there are challenging, interesting and adequately funded research projects for them to work on.
The Universities cannot generate such projects by themselves, in isolation.

I believe that it is in the interests of all parties that a dose of the "real world's problems" is added to the "scientific method" as a paradigm for training in applied research.