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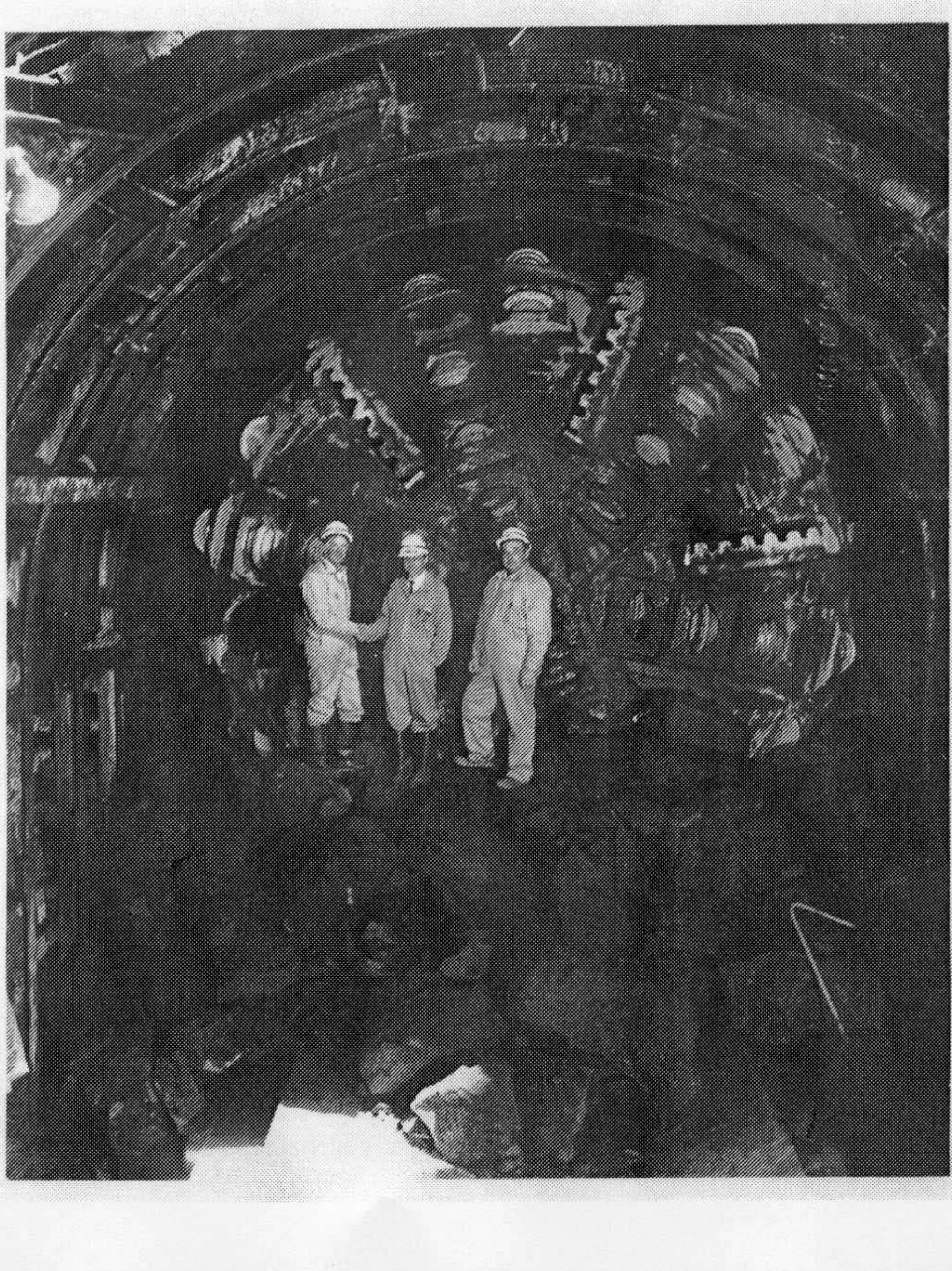


"MEASUREMENTS OF CUTTING FORCES DURING MACHINE TUNNELLING"

APPLIED RESEARCH WORK BY MELBOURNE UNIVERSITY

Due to the nature of the rock cutting process during full-face tunnel boring, the force applied by a disc cutter may be expected to vary as it rolls over the surface of the rock. When the force exceeds that required to cause tensile or shear failure of the rock surface, a chip will be formed and be pushed free. The transmitted force will then suddenly drop, and then gradually build up again to that required to cause rock failure.

The stress distribution caused by an edge-loaded disc pressed into a rock surface is much more complex than that produced in an axially-loaded cylinder during an unconfined compression test, so it is not surprising that using the unconfined compressive strength to predict the optimum loading upon disc cutters is not always successful. If the forces required to cause failure of a rock mass by the disc cutters on a full-face tunnel boring machine could be measured, and compared with the laboratory-measured strength of the same rock, the validity of predictor equations could be much improved.

The University of Melbourne has been conducting cooperative research on machine tunnelling with the MMBW since 1979, working in the laboratory, in Stage 4 of the Thomson-Yarra Tunnel, in the Anderson Road Drain, and now in the Western Trunk Sewer tunnel.

The previous projects, which were under the sponsorship of the Robbins Company, studied the force distribution on a disc cutter shaft using mathematical modelling, and identified the positions of maximum stress concentration.

Cutter force dynamometers (strain-gauged disc cutters) were designed and constructed. After FM telemetry proved to be unsatisfactory for the transmission of data in the Thomson-Yarra Tunnel, another technique involving "hard-wired" connections from the disc cutters to a tape recorder proved to be partially successful in the Anderson Road Drain.

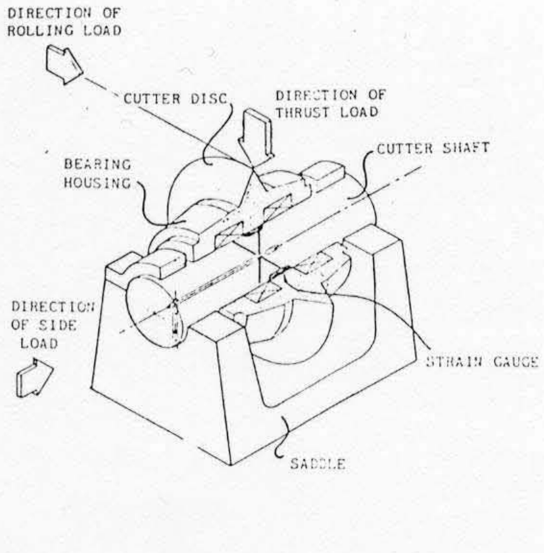
The Western Trunk Sewer Project includes 15.3 km of 5.6 m diameter tunnel, and a Robbins shielded full-face tunnel boring machine commenced excavating 13.5 km, through both homogeneous and vesicular basalts, in late 1985. The machine applies a total axial thrust of 600 tonnes, through 39 disc cutters.

If this force was uniformly distributed each disc cutter would transmit a force of 15.4 tonnes to the rock face. The actual variations of force with time and rolling distances have been successfully measured during this project, using new instrumentation.

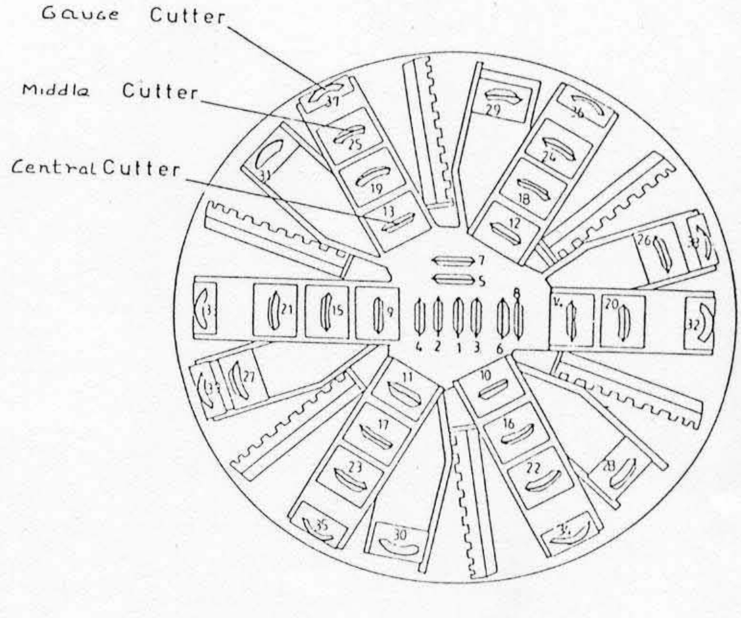
The shafts of 3 disc cutters were converted into force dynamometers, by the installation of strain gauges at the optimum locations, chosen from the previously - mentioned mathematical modelling. At each strain gauge position a shallow recess was cut onto the outside of the cutter shaft, and the strain gauges were glued on. The shaft is an integral part of the disc cutter, which slowly rotates in a bearing as it rolls over the surface of the rock, under applied forces of the order of several tens of tonnes.

The strain gauges, mounted on the surface of the shaft, must be protected from the hot oil in which the bearing is bathed, as well as from the effects of the mechanical and frictional stresses. A silastic coating provides electrical and thermal insulation, and an epoxy resin coating provides mechanical protection. Electrical connections from the strain gauges are made via holes drilled inwards from each strain gauge position to intersect an axial hole running along the shaft.

The disc cutters in positions number 13 (called the "inner" cutter), number 25 (called the "middle" cutter) and number 37 (called the "gauge" cutter) were instrumented. The output from the strain gauges is only 0.52 millivolts per tonne of load on the disc cutter, and the environment for the transmission of such

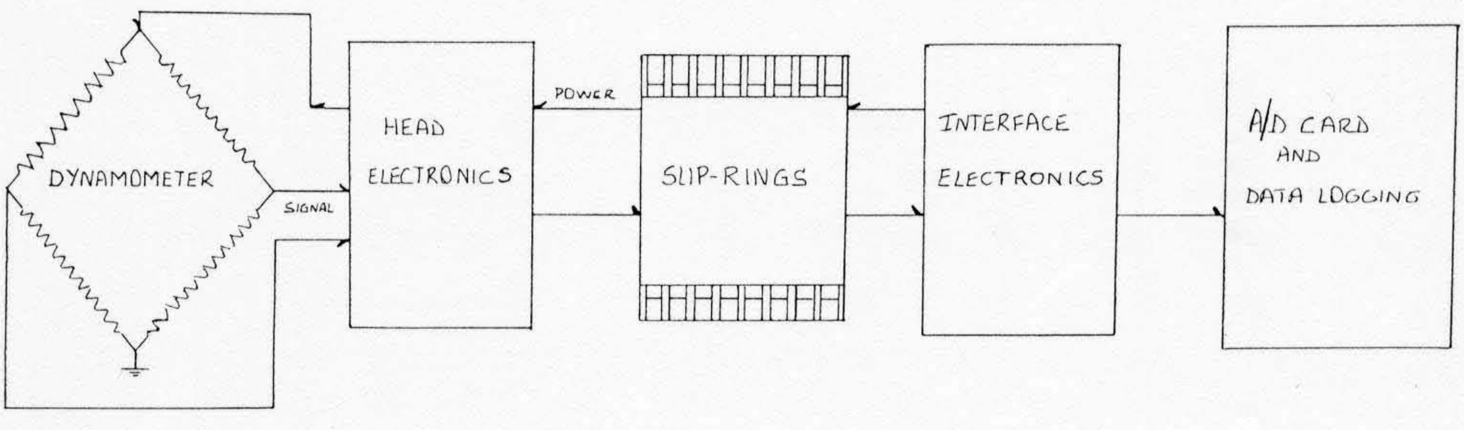


Details of the Dynamometer



Inside View of Cutting Head of T.B.M.
Showing Cutter Positions and where
Dynamometers were Located
(Courtesy of the M.M.B.W.)

ELECTRONICS FLOW CHART



- STRAIN GAUGES BRIDGES.

  FORCES:
  - THRUST
  - ROLLING
  - SIDE.

- AMPLIFIER.
- VOLT TO FREQUENCY CONVERTER

- TRANSFER POWER AND SIGNAL.

- POWER SOURCE.
- FREQUENCY TO ANALOGUE VOLT CONVERTER
- AMPLIFIER
- LOWER PASS FILTER

- ANALOGUE TO DIGITAL CONVERTER (A/D)
- XT PERSONAL COMPUTER

small DC signals through the tunnel boring machine, powered by 11 kiloVolt electricity, frequently subjected to large fluctuations and heavy machine vibration, would be very noisy.

So a Head Electronics Box, mounted on the inside of the rotating head of the tunnel boring machine, amplifies the strain gauge output signals 124 times, and then converts them linearly to a frequency in the range 0 to 10 kiloHertz.

The FM signals are taken from the head of the tunnel boring machine, rotating at 5.7 rpm, through a series of Slip-Rings mounted coaxially with the head, to the Interface Electronics Box, mounted on the non-rotating body of the machine. This Box supplies stabilized power to the Head Electronics Box, and converts the signals received back from it from frequency to linear analogue voltage. The analogue signals are amplified, and any signal noise created during the conversion is filtered out.

These signals are then transmitted to a Personal Computer temporarily housed in the crib room on the tunnel train. They are converted by means of an Analogue to Digital Converter Card (A/D Card), which accepts voltages in the range of -5 Volts to +5 Volts and linearly converts them to binary numbers in the range 0 to 4095. The Computer reads 5 input channels, each with a maximum speed of 216 data points per second, and stores the data at a rate of 2 kB/sec, allowing a maximum uninterrupted recording time of 5 minutes to fill the computer's RAM memory. The 5 channels read are the thrust force and rolling force from the "inner cutter" (permanently-connected), and the side, rolling and thrust forces from either the "middle" or "gauge" cutter (selected by the operator).

The major advantages of using a Personal Computer as a data logger derive from the ability to :

get a visual display of the data as it is being recorded, so checking its quality and validity;

manage and manipulate data without having to transfer data to another device;

transfer data directly to another computer, e.g. the VAX Cluster at Melbourne University;

add information from other computers, e.g. the MMBW's tunnel boring machine data logging system, which continuously records "global" machine performance, such as total thrust, power consumption, penetration rate, direction of thrust vector, etc.

Between August and November 1987, as the tunnel boring machine was driving the tunnel eastwards from Kororoit Creek to Brooklyn, good quality recordings of force measurements were made. They show patterns of rapidly fluctuating peaks of the thrust forces being applied through the disc cutters. Each peak is presumed to be a record of one episode of rock failure and chip formation.

The preliminary analyses have concentrated upon the upper quartile peak thrust forces (i.e. values exceeding about 75% of the peaks), the extreme peak thrust forces, and the frequency of peak forces. The latter also indicates the circumferential rolling distances between chip formation episodes, as a function of head rotation rate, radial distance of a cutter from the centre of the head, and time between successive thrust force peaks.

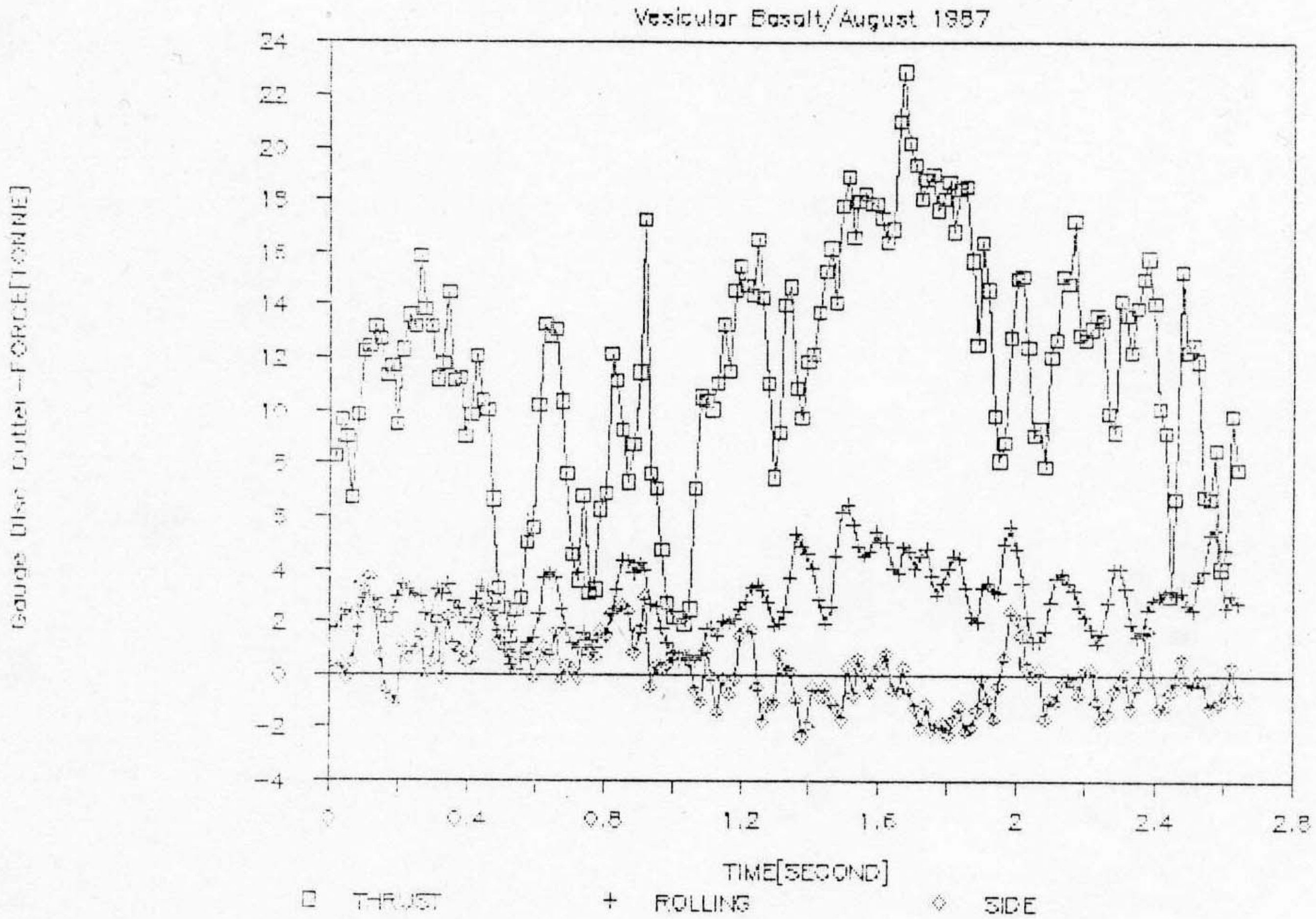
These preliminary analyses may be summarised as follows, for both homogeneous and vesicular basalts.

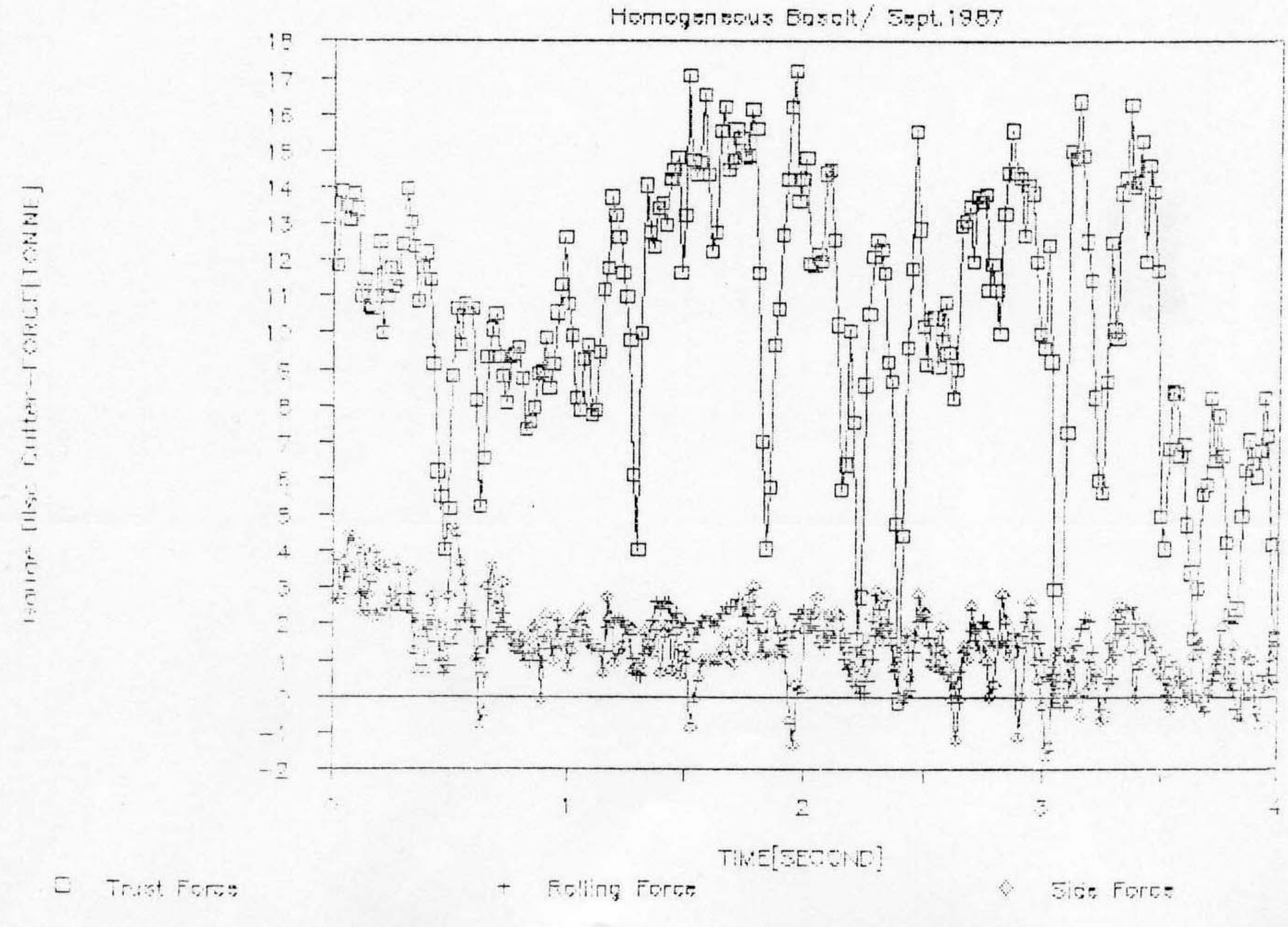
Cutter Position	"Gauge"	"Middle"	"Inner"
"Upper Quartile" Peak Thrust Force	12 - 14 tonnes	12 - 14 tonnes	16 - 18 tonnes
"Extreme" Peak Thrust Force	16 - 18 tonnes	16 - 18 tonnes	24 - 28 tonnes
Peak Force cycles/sec	8	10	10
Peak Force rolling distances	210 mm	90 mm	30 mm

This shows that the measured magnitudes of thrust forces on individual cutters are up to 81% higher than the "global" average of 15.4 tonnes thrust per cutter.

The "inner" cutter applies the highest peak thrust forces to the rock, and apparently produces the smallest chips of rock : 30 mm in length dimension;

MMBW--WESTERN TRUNK SEWER PROJECT





the "gauge" cutter applies lower peak thrust forces to the rock, and apparently produces the largest chips of rock : 210 mm in length dimension.

This indicates that the specific energy of cutting is much lower (and the efficiency much higher) for the "gauge" cutter than for the "inner" cutter position.

Comparisons of the patterns of thrust forces recorded in homogeneous basalt with those recorded in vesicular basalt show that the latter is much more variable in strength, containing weaker patches which require lower cutting forces between patches of strong rock which require forces as high as any recorded in the homogeneous basalts. This strength pattern is in agreement with that expected from geological inspection.

Detailed comparisons are expected to be made between the cutter force measurements and laboratory tests on cores drilled from the tunnel walls at the locations where the forces were measured.

At the time of writing, in January 1988, the tunnel boring machine is being reassembled at Sayers Road, and is expected to resume tunnelling in February, westwards towards Hopper's Crossing. New instrumented cutters are being built, and the electronic data acquisition system is being refurbished. The cutting force measurements are expected to yield more valuable information during the next tunnel drive, including the cutting forces experienced when cutting mixed faces of hard basalt and clay seams.

Melbourne University personnel currently involved in this project are Juan Jofre and Dr. Bill Bamford; those previously involved include Alex Duran, Dr. Andrew Samuel, L. P. Seow, and Nigel Sugden.

The assistance of MMBW personnel Bob Cooper, John Coulsell, Peter Hunter, Bernie Parker, Ray Sanders and Ernie Watson is gratefully acknowledged.