TUNNEL BORING MACHINE INSTRUMENTATION

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ABSTRACT

Tunnel Boring Machine Instrumentation

A 9.17 m. diameter tunnel boring machine presently in operation in Chicago, Illinois, has been instrumented to continuously monitor and record machine thrust, torque and penetration rate during boring. A micro-processor-based data logger capable of monitoring up to 60 channels of data digitizes and converts into appropriate engineering units the signals from various transducers mounted on the machine. The output from the data logger is sent to a teleprinter, providing a permanent record of measured data. The program control enables the data logger to scan all data channels at desired time intervals. Data obtained to date have been analyzed to determine the interrelationships of the parameters measured. Penetration rate was found to increase linearly with machine thrust with a unit increase in thrust causing more than a unit increase in penetration rate. For low thrust levels corresponding to the initial stages of a boring cycle, the penetration rate was observed to behave erratically until the thrust pressure was sufficiently high for the cutters to establish full contact with the tunnel face. Torque showed a curvilinear increase with machine thrust, reaching the design rating at about 70% of maximum available thrust. No-load torque was approximately 20% of the machine's rated torque capacity. Overall, the trends observed in measured machine parameters correlated closely with those predicted from experimental and theoretical boreability studies. In summary, the instrumentation system has met two basic goals. First, it provided extensive and accurate boring data and secondly, it has proven that an automatic data acquisition system can be installed on a TBM and can function under adverse environment.

INTRODUCTION

Mechanical tunnel boring is gaining widespread recognition as a rapid, effective means of underground excavation. Where favorable conditions exist, tunnel boring machines (TBMs) are capable of attaining high advance rates at greatly reduced costs compared to conventional drill and blast methods. Their successful application to hard rock boring is still limited, however, due to slow cutting rates coupled with high cutter wear. But, continued improvements in the design and operation of TBMs together with introduction of newer, more wear resistant materials for cutting tool structures are expected to allow the economical utilization of these machines in boring rocks of much higher strength than those considered feasible today.

An effective means of improving TBM performance is to analyze and evaluate field boring data obtained from past and present tunneling projects. A detailed analysis of such data can provide answers relating to the interrelationship of parameters influencing machine performance. The information gained can then be used as a guide for selecting the optimum combination of these parameters to realize maximum boring efficiency.

Although collection and analysis of boring data have been pursued by numerous investigators as well as machine manufacturers, several barriers inherent to field data collection have limited the success of such attempts. Despite the fact that most tunneling contractors together with the manufacturers maintain extensive boring records, some caution must be exercised in employing these records as there exists a degree of uncertainty regarding the accuracy of the data. Several factors can contribute to collection of inaccurate boring data by the contractors. First, the boring logs maintained by most contractors generally do not include all of the data necessary for conducting detailed field boreability investigations. Moreover, some of the data recorded may be inaccurate. Manufacturers generally supply their machines with inexpensive instrumentation as they are primarily concerned with monitoring machine components for overload conditions rather than obtaining data for detailed analysis. In addition, these gauges and meters are generally not well protected from the tunnel environment and after several months of underground operation, their accuracy is questionable. Second, most field boring data does not reflect the actual penetration rate achieved by the machine at a given time. The penetration rate calculated and recorded by the operator is usually an average for the given mining shift. This includes the inefficient boring by the machine that is the result of reducing the thrust pressure due to ground conditions or mechanical difficulties with the boring machine or back-up equipment. Furthermore, if the machine time clock is used to measure the boring time, this may add another error to the calculated penetration rate since on some machines the time clock also records the unproductive boring time consumed at the beginning and end of a boring cycle when the cutterhead is rotated several extra revolutions to pick up the remaining muck from the tunnel invert.

There are a few options in collecting accurate and complete field boring data, one of which is the utilization of an automatic data acquisition system to measure and record the desired boring parameters. This paper presents and discusses the findings of a field instrumentation program carried out by means of a data acquisition system installed on a TBM presently in operation in Chicago, Illinois.

FIELD INSTRUMENTATION PROGRAM

Description of the Tunnel Boring Machine

The machine instrumented was a 9.17 m. diameter Jarva tunnel borer owned and operated by Kenny-Paschen-S & M, a Joint Venture of Kenny Construction Company, Wheeling, Illinois; Paschen Contractors, Inc., Chicago, Illinois; and S & M Constructors, In., Solon, Ohio. The machine is boring a 8,458 m. long tunnel as part of the Tunnel and Reservoir Plan (TARP) of the Metropolitan Sanitary District of Greater Chicago.

The machine is equipped with 64 single disc cutters of 39.4 cm. diameter in addition to a center cutter containing 4 discs of 30.5 cm. diameter. The maximum thrust rating is 13,344 KN and it can generate a maximum torque of 4,252 KN.m at a cutterhead speed of 4 RPM. A picture of the model of this machine is shown in Figure 1.

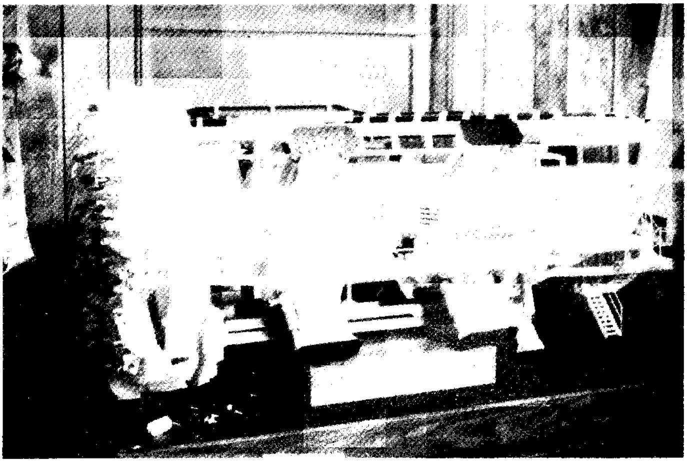

Figure 1 - View of the model of Jarva tunnel borer which was instrumented.

Description of the Data Acquisition System

The purpose of instrumentation was to accurately and continuously monitor machine performance including thrust, torque, and penetration rate during the actual boring operation.

At the outset, it was decided that the data acquisition system to be placed on the machine should meet the following requirements: 1) It should be an automatic system to permit program control and remote operation; 2) The system should provide instant output as it measures the machine operating parameters to allow the operator or other tunnel personnel to observe the precise values of thrust, torque, and penetration rate; 3) It should be rugged enough to withstand the adverse tunnel environment and to avoid damage from vibration or dust, and, 4) The system should incorporate flexibility so that more channels of input can be added in the future, if desired.

After an extensive review of the currently available data acquisition systems, it was concluded that a data logger in conjunction with a teleprinter would meet the requirements and be able to accept input from a variety of transducers. Although such a system has never been used in an underground environment, it was believed that adequate protection could be provided to avoid damage from vibration or dust.

The instrumentation system consisted basically of four main components; a data logger, a teleprinter, transducers, and signal conditioning and amplifier units.

The data logger used was a Fluke Model*2241 B unit. In operation, the data logger accepts an input signal, e.g. DC current, DC voltage, AC voltage, and when assigned a range or measurement scale, compares this input to the scale then outputs a signal in terms of voltage or engineering units to a recording device. The input signal is received through a high speed scanner which is actuated at preset time intervals by program control. The system flexibility allows continuous scanning of all channels at desired time intervals, as well as a single scan of one channel or continuous monitoring of a single channel. The scanning speed can be programmed as high as 15 channels per second. The data logger also incorporates alarm limits which are actuated when an input signal exceeds its preselected limit. In case of power loss, the data logger maintains its programming commands by switching to an internal battery. The unit, as purchased, had the capacity of monitoring 60 channels of data simultaneously. The data logger frame, however, included provisions for expansion to 1000 channels of data.

The teleprinter, which was a Teletype Model* 43 printer, receives the output from the data logger and prints it on a 28 cm. wide fanfold

*Not meant as an endorsement; referrals to brand names are made for identification purposes only.

paper, producing one original and one copy. The printhead mechanism is a nine-wire matrix impact type with a self-inking ribbon to provide clear, distinct figures. The data logger can be remotely programmed through the printer. Figure 2 shows a picture of the data logger and the printer.

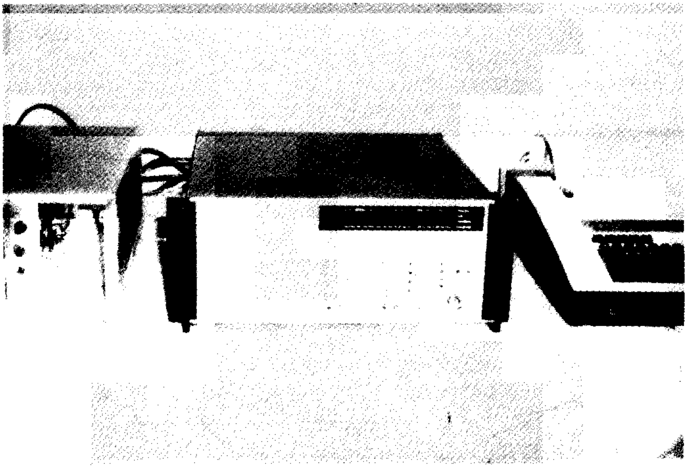

Figure 2 - The data logger and teleprinter used for instrumentation.

Once the data logger and the teleprinter were chosen, the next step was to select the transducers for measuring the desired machine operating parameters. As noted earlier, it was intended to measure the machine thrust, torque, and penetration rate during boring. The chief requirement in selecting the transducers was that they be rugged enough to withstand the severe tunnel environment.

A diaphram type pressure transducer was selected to measure the hydraulic oil pressure and thereby the thrust generated by the machine. This transducer was rated at 34.5 MPa maximum pressure. The penetration rate was measured by monitoring the forward movement of the cutterhead with respect to the machine grippers that are stationary during boring. The transducer used was a linear potentiometer which provided an electrical signal proportional to the length of cable attached to the transducer potentiometer. The transducer did not directly measure the penetration rate but rather produced the forward movement of the cutterhead at preselected scanning intervals. Knowing the scanning interval, it was then possible to calculate the machine penetration rate. The machine torque was measured by monitoring the amperage on one of the cutterhead drive motors. The transducer used was a current transformer in the shape of a donut encircling one phase of the motor control. The transformer employed a 8500:1 current stepdown ratio which was necessary to bring the motor current (170 amps maximum) down to a level acceptable by the data logger.

As noted earlier, the data logger incorporated built-in, linearization scales for converting the input signals into appropriate engineering units. Based on the sensitivities supplied with the transducers, the necessary conversion scales were programmed into the data logger so that each channel output was in the desired engineering units.

The last system component was the signal conditioners with built-in amplifier circuits. These units were used in conjunction with the pressure and displacement transducers to supply the strain gage bridge voltage, and to amplify the bridge output signal to desired levels.

The entire data acquisition system was assembled, calibrated, and checked in the laboratory prior to field operation. To protect the data logger, the teleprinter and the signal conditioner units from the adverse tunnel environment, a wooden box was built to house these units in the tunnel. The box was constructed from plywood and coated with sealant material to prevent moisture and dust from entering the box and therefore damaging the sensitive electronics package. In addition, the shelves supporting each system component were covered with thick foam trays to dampen vibration and to protect the equipment from high shock loads caused by machine operation.

The wooden box housing the data logger, the teleprinter, and the signal conditioning units was placed in a room at the rear of the machine (Figure 3). This room was originally used for housing the main transformers, but was emptied when the contractor moved the transformers back on the trailing unit. This room was the most protected and one of the few large working areas on the machine. For these reasons, it was selected to house the instrumentation cabinet.

The pressure transducer was connected into the hydraulic line supplying the operator console's thrust pressure gauge. The transducer was placed in a secure area to provide protection from any damage that might be caused by the working environment (Figure 4). The displacement transducer, as previously described, was attached between a movable and a stationary part of the machine. One criterion for the selection of an appropriate site for placement was that it should be in a remote area so that the transducer cable is not damaged accidentally by tunnel personnel. To meet this requirement, the transducer was placed beneath the machine torque tube at a height of about 3 m. from the tunnel invert (Figure 5). This location served two useful purposes. First, the transducer was totally protected from any falling rock by the torque tube above it and secondly, its 3 m. height provided maximum protection from

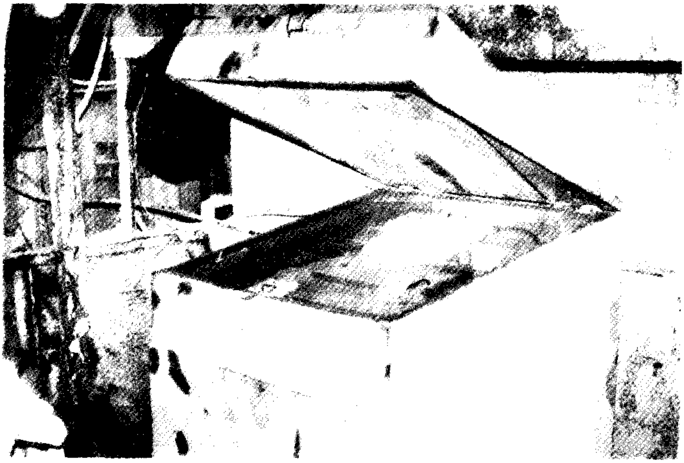

Figure 3 - The cabinet used for housing the data acquisition system on the TBM.

possible damage by the tunnel personnel. The current transformer was placed inside the main electrical cabinets and encircled one phase of motor control for one of the cutterhead drive motors (Figure 6). Being inside a cabinet thus protected the unit from the adverse tunnel environment.

The total instrumentation package was installed on the machine when it was down for maintenance and cutter changes. This was necessary since due to its size and power, it was extremely difficult to work around the machine while it was boring.

The initial attempt to monitor the machine's performance with the automatic data acquisition system was only partially successful due to a malfunctioning amplifier on the signal conditioner used for supplying the voltage to the pressure transducer strain gage bridge and conditioning the signal. This caused considerable drift in output from the pressure transducer, producing erroneous readings. Also encountered were transducer shielding problems causing noise interference in input signals. Both of these problems, however, were corrected after extensive effort. The amplifier circuit of the malfunctioning signal conditioner was returned to the manufacturer and repaired. The transducers and the cables were shielded and grounded which completely solved the noise interference problem. After these changes, the total system was found to operate satisfactorily.

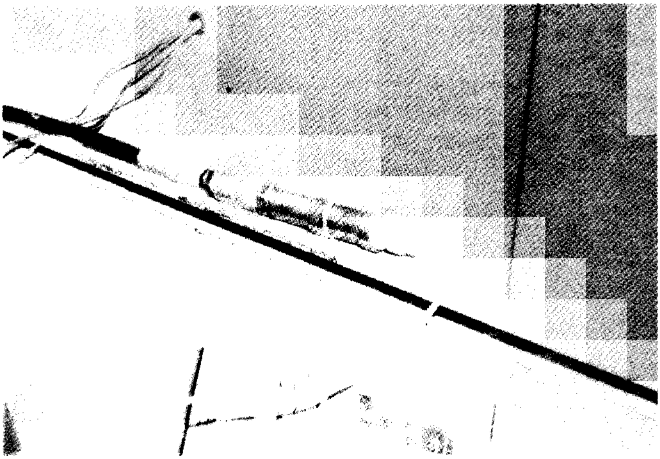

Figure 4 - The pressure transducer used for measuring TBM thrust pressure.

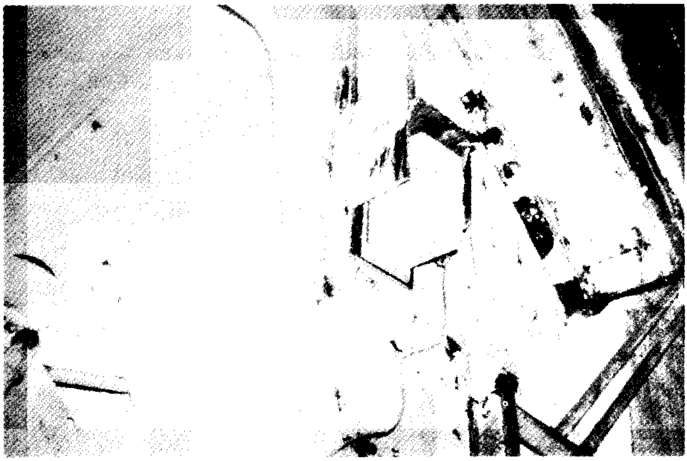

Figure 5 - The displacement transducer mounted on rear set of grippers.

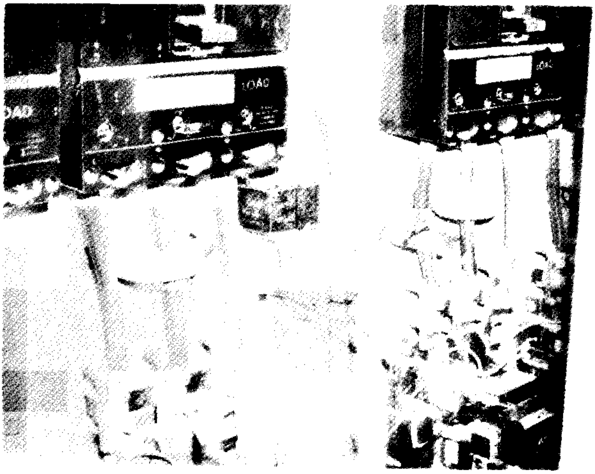

Figure 6 - The current and voltage transformers inside the main electrical cabinets on the TBM.

Although not originally planned in the instrumentation program, another channel of data measured was the voltage on the drive motor monitored for current. This was requested by the machine manufacturer to determine any voltage drop on the motor during boring. This was accomplished with a voltage transformer which simply reduced the line voltage to a level that can be input into the data logger. This transformer can be seen in Figure 6 on the left side of the current transformer.

Results of the Instrumentation Program

As previously described, the data logger through remote control from the teleprinter could be programmed to scan all channels at desired time intervals. Therefore, data acquisition was conducted at different scanning intervals based on the data collection requirements. During normal machine operation, a 15-minute scanning interval was chosen which proved to be adequate for monitoring machine operation over long periods of time. Also undertaken was fast scanning of data channels at the beginning of several new boring cycles. This was done to measure the machine penetration rate and torque at various levels of thrust as the machine was brought up from virtually a zero thrust condition to its normal operating thrust level. A five-second scanning interval was used for this data collection.

Since in operation, the automatic data acquisition system has provided extensive data relating to machine performance. Table 1 shows representative samples of data outputs produced by the teleprinter. Both samples of data with fast and slow scanning rates are included in the table. As can be seen, each scan is initiated with date and time as programmed into the data logger. Following this is an identification number which in this case refers to the machine identification number designated by the manufacturer. The next line of data contains the channel number and the reading in that channel. The first column, (Channel 0) reflects the measurement by the pressure transducer, indicating the hydraulic pressure at the time of scanning. The second column, (Channel 1), indicates the displacement of the cutterhead with respect to a stationary part, which was the machine grippers. Note the decreasing displacement reading as boring proceeds. This was due to the location of the displacement transducer as it measured the distance between the rear set of grippers and the back of the torque tube which moved forward with the cutterhead during boring. The transducer could be mounted between the cutterhead and the front set of grippers and thus provide positive displacement, but it was believed that this location could present potential damage to the transducer especially during cutterhead maintenance and cutter changing operations. The stepped-down drive motor voltage is indicated in the third column, (Channel 2). The voltage transformer reduced the motor voltage by a factor of approximately 12, thus the voltage readings produced by the instrumentation system were multiplied by 12 to determine the actual motor voltage. The last column reflects the drive motor amperage reading measured as a millivolt output corresponding to motor amps.

Following the collection of extensive boring data by the data acquisition system, the next step was to plot the interrelationships between several parameters. To accomplish this, the data required further manipulation to put it into final form in terms of thrust, torque, and penetration rate. The data logger through its programming capabilities could have performed this final conversion, however, this was not desirable. The reason for this was that if the data logger was programmed to make the conversion, an assumption had to be made in regard to the number of thrust cylinders and drive motors operating during boring. Since during field study, it was observed that the machine did not always run with all of its thrust cylinders or drive motors operational, the data logger would then provide inaccurate data. By measuring the thrust pressure and drive motor amps, however, one could easily determine the machine thrust and torque by knowing the number of working thrust cylinders and drive motors at the time of data acquisition.

The thrust generated by the machine was determined by multiplying the measured thrust pressure by the area of a thrust cylinder times the number of thrust cylinders in operation. The penetration rate was calculated from the cutterhead forward displacement measurements by dividing the incremental displacement reading by the time interval. The drive motor voltage was determined by multiplying the voltage

Table 1 - Sample of data output from the teleprinter

```
Y711:03:04
X  3001
A  0 +  2933PSIG  A  1 + 60.19INCH  A  2 +35.686 V   A 10 + 7.291MV


Y711:03:19:06
X  3001
A  0 +  3009PSIG  A  1 + 37.06INCH  A  2 +35.755 V   A 10 + 6.282MV


Y711:03:34:06
X  3001
A  0 +  3036PSIG  A  1 + 23.32INCH  A  2 +36.039 V   A 10 + 7.588MV


Y711:03:49:06
X  3001
A  0 +    32PSIG  A  1 + 37.78INCH  A  2 +39.109 V   A 10 + 0.004MV


Y711:04:04:06
X  3001
A  0 +    19PSIG  A  1 + 52.09INCH  A  2 +39.037 V   A 10 + 0.003MV


Y711:04:19:06
X  3001
A  0 +  2960PSIG  A  1 + 33.23INCH  A  2 +36.320 V   A 10 + 6.680MV


Y711:04:34:06
X  3001
A  0 +  2869PSIG  A  1 + 10.90INCH  A  2 +36.410 V   A 10 + 7.061MV


Y711:04:49:06
X  3001
A  0 +  3116PSIG  A  1 + 64.13INCH  A  2 +36.068 V   A 10 + 8.051MV


Y711:05:04:06
X  3001
A  0 +  3038PSIG  A  1 + 39.82INCH  A  2 +35.961 V   A 10 + 7.028MV


Y711:05:19:06
X  3001
A  0 +  2906PSIG  A  1 + 28.06INCH  A  2 +36.254 V   A 10 + 6.515MV
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reading by 12 which was the reduction factor for the voltage transformer. The last parameter which was the machine torque, was calculated from the amperage readings on one of the cutterhead drive motors. The amperage was first converted to motor horsepower output using a chart provided by the motor manufacturer. To determine the cutterhead torque, this value was then multiplied by the number of drive motors running at the time of data acquisition and the resultant value, the cutterhead horsepower, was divided by the cutterhead angular velocity, thus giving the cutterhead torque. In these calculations, it was assumed that all the drive motors were supplying the same amount of torque to the cutterhead. This was not actually true since the amperage on each drive motor was observed to constantly fluctuate depending on the cutterhead position during boring, and other related factors. However, through discussions with the manufacturer and the contractor, it was concluded that a cutterhead torque value which was calculated based on the torque measurements of one drive motor should be very close to actual cutterhead torque. Thus the cutterhead torque as determined using the aforementioned procedure is believed to represent the actual torque very closely. A precise measurement of the cutterhead torque requires the instrumentation of each drive motor which was not feasible within the scope of this instrumentation program.

Table 2 presents some of the data in its final form and ready for analysis. Figures 7 through 11 display the graphical relationships of the parameters measured. A plot of machine thrust versus rate of penetration is shown in Figure 7. The trend depicted in this figure is very similar to that predicted from laboratory studies and also those reported by other investigators involved in boreability studies. As was expected, over the operating thrust range of the machine, a unit increase in thrust causes more than a unit increase in the rate of penetration. Also, note the large variation of data for low thrust values. The data within this low thrust range was measured at the beginning of a new boring cycle when the machine was not in full contact with the rock face. Until full contact was established, the machine forward movement was rather erratic thus causing a large variation in the rate of penetration. Figures 8 and 9 show the behavior of drive motor amps and the cutterhead torque with increasing machine thrust. The trends depicted in these figures are as expected, indicating a curvilinear relationship between the cutterhead torque and the machine thrust. Also shown in these figures is the no-load torque which appears to be about 15 to 20% of the machine's rated torque capacity of 4,252 KN.m.

A rather unique observation can be made from the torque versus thrust graph. It is seen that at a machine thrust of about 8,896 KN. which is approximately 70% of available maximum thrust, the torque required to rotate the cutterhead at the RPM used approaches and occasionally exceeds the rated torque capacity of the machine. This leads to the conclusion that this particular machine in boring through limestone is essentially torque limited. This observation confirms

Table 2 - Sample of derived data from the TBM instrumentation

Date	Time	Machine Thrust(N)	ROP (m/hr)	Motor Voltage	Motor Current (amps)	Estimated Horsepower (KW)	Estimated Torque(N.m)
7-10-78	17:10:59	9,544,296	2.16	446.5	166.4	1762	4,187,278
7-10-78	17:11:59	9,347,472	2.22	444.1	151.7	1597	3,796,222
7-10-78	17:12:59	9,157,320	2.21	441.3	161.2	1703	4,048,945
7-10-78	17:13:59	9,314,112	2.19	443.1	141.0	1477	3,511,576
7-10-78	17:14:59	9,574,320	2.18	443.2	166.4	1762	4,187,278
7-10-78	17:15:59	9,210,696	2.19	442.6	162.2	1709	4,075,092
7-10-78	17:16:59	9,260,736	2.25	445.0	168.8	1788	4,251,124
7-10-78	17:17:59	9,360,816	2.24	443.0	160.3	1693	4,023,688
7-10-78	17:18:59	9,160,656	2.23	442.5	182.4	1941	4,612,175
7-10-78	17:19:59	8,983,848	2.21	443.8	168.6	1786	4,245,257
7-10-78	17:20:59	9,287,424	2.27	444.9	150.1	1579	3,752,488
7-10-78	17:21:59	9,527,616	2.27	445.8	162.6	1719	4,085,727
7-10-78	17:22:59	9,537,624	2.19	444.6	146.0	1533	3,644,362
7-10-78	17:23:59	9,023,880	2.20	446.3	139.6	1462	3,474,333
7-10-78	17:24:59	9,354,144	2.19	446.3	139.6	1462	3,474,333
7-10-78	17:25:59	9,367,488	2.19	444.0	144.4	1515	3,602,025
7-10-78	17:26:59	9,334,128	2.18	442.6	140.6	1473	3,500,936
7-10-78	17:27:59	9,514,272	2.14	444.7	158.4	1672	3,974,459
7-10-78	17:28:59	9,140,640	2.13	446.6	161.5	1706	4,056,926
7-10-78	17:29:59	9,214,032	2.16	445.7	177.6	1887	4,485,225
7-10-78	17:30:59	8,960,496	2.21	444.0	142.5	1494	3,551,480
7-10-78	17:31:59	9,297,432	2.19	443.7	165.3	1749	4,158,016
7-10-78	17:32:59	9,310,776	2.18	446.3	148.4	1661	3,947,799
7-10-78	17:33:59	9,397,512	2.19	447.2	162.2	1715	4,075,548
7-10-78	17:34:59	9,420,864	2.16	443.6	153.9	1621	3,854,748
7-10-78	17:35:59	9,397,512	2.15	446.5	142.5	1491	3,543,500
7-10-78	17:36:59	9,107,280	2.14	444.0	148.9	1565	3,721,736

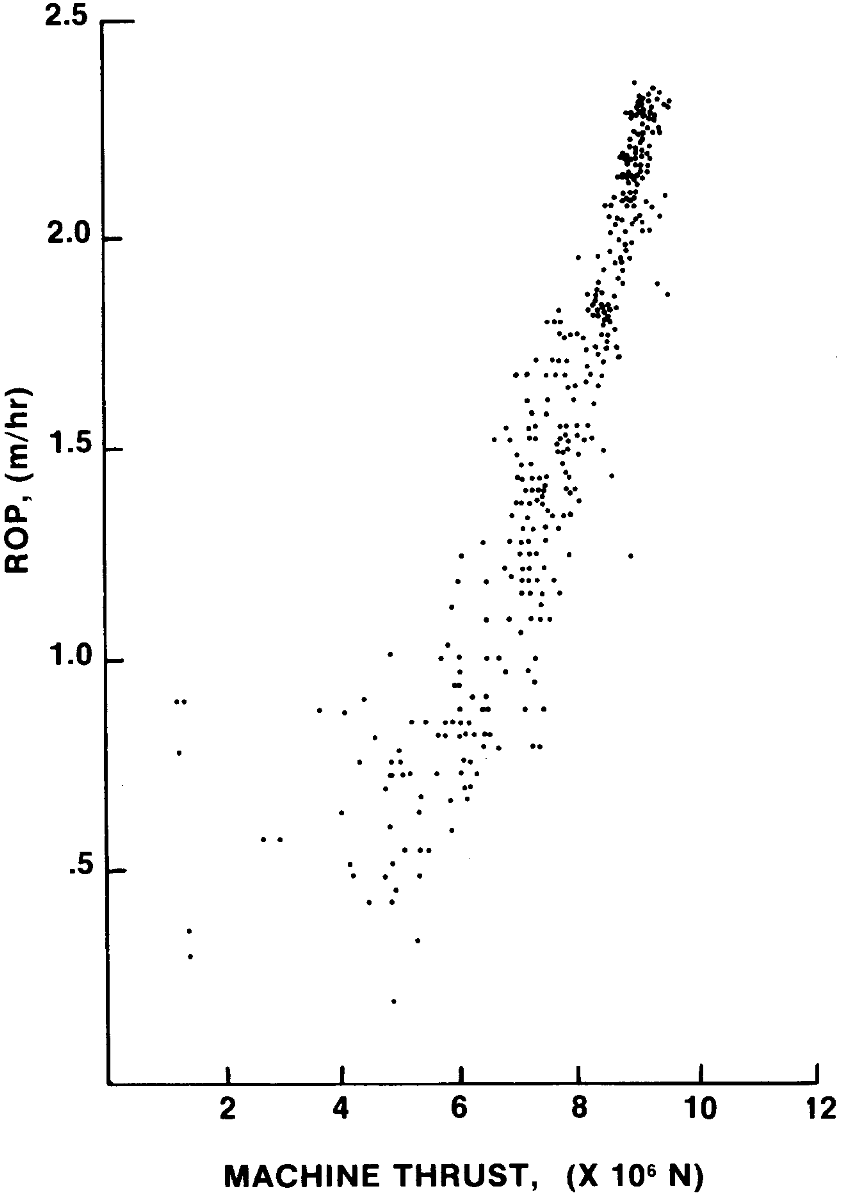

Figure 7. Machine Thrust vs. Rate of Penetration for the 30 ft. diameter Jarva TBM Operating in Chicago, Illinois.

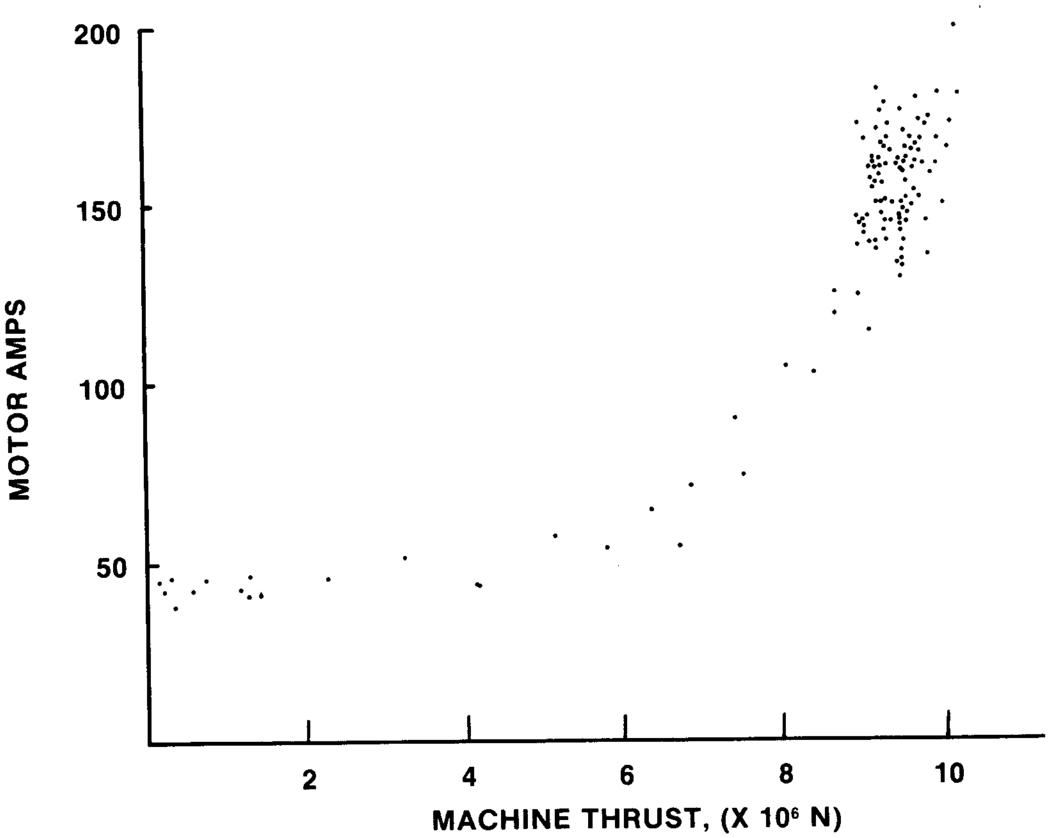

Figure 8. Machine Thrust vs. Amps (on Drive Motor No. 11) for the 30 ft. diameter Jarva TBM operating in Chicago, Illinois.

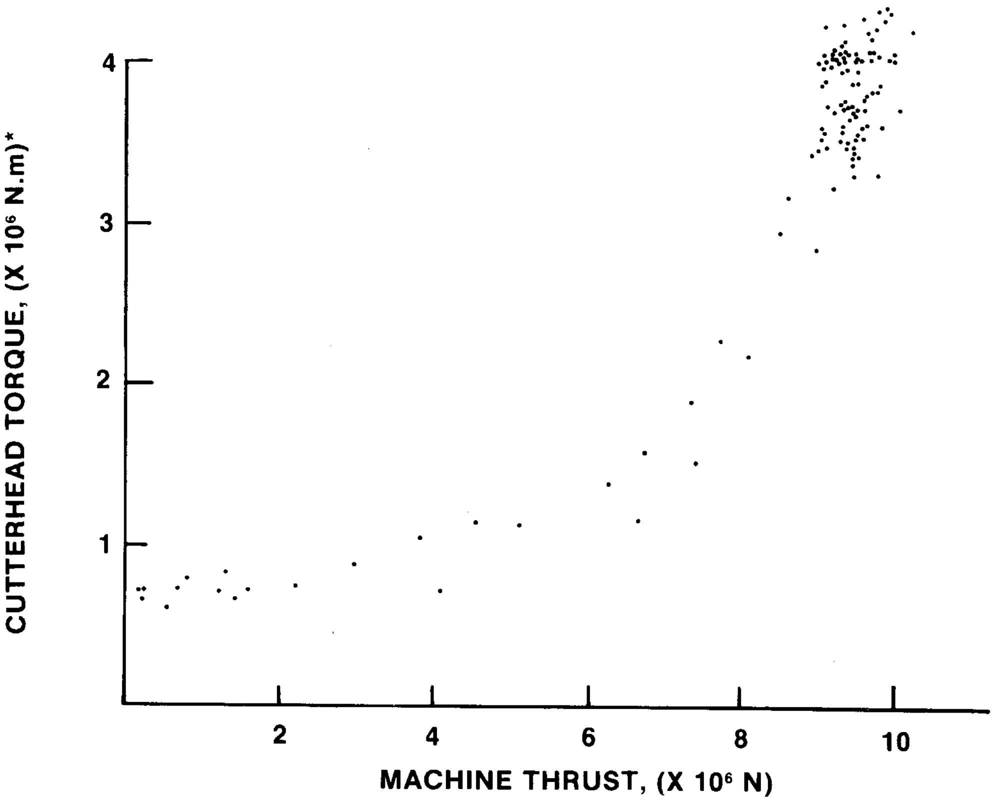

Figure 9. Machine Thrust vs. Cutterhead Torque for the 30 ft. diameter Jarva TBM Operating in Chicago, Illinois.

** Calculated from data measured for Drive Motor No. 11 on the machine.*

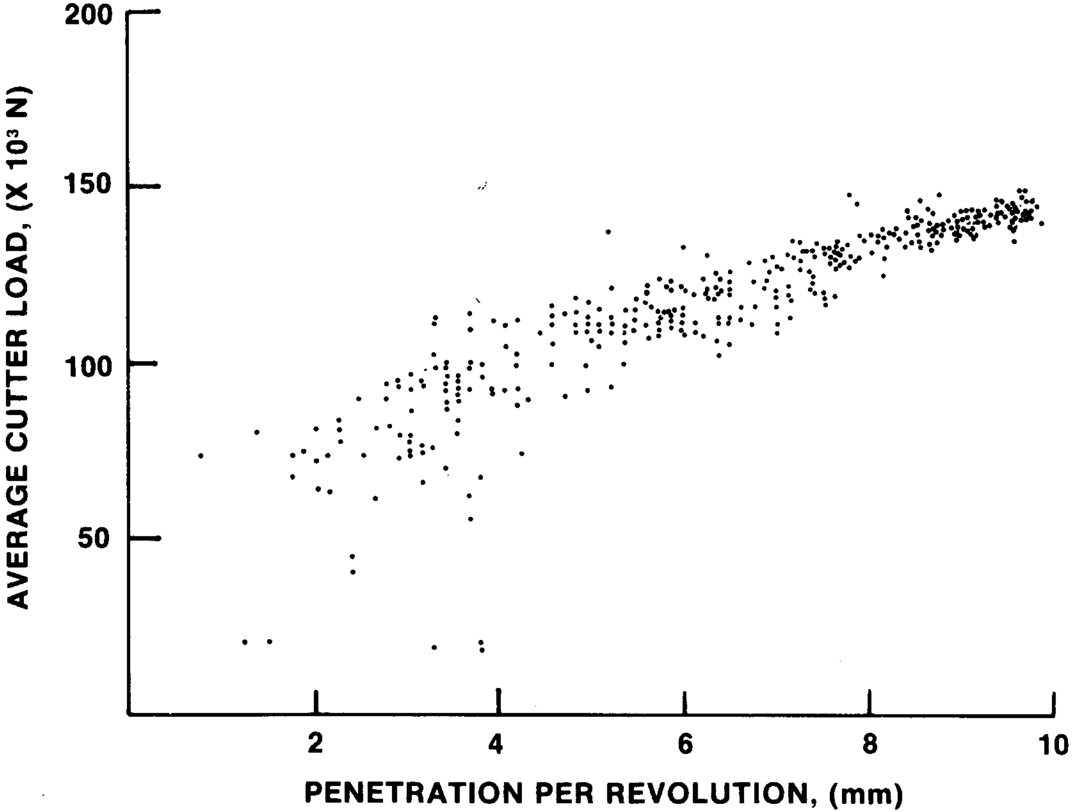

Figure 10. Average Cutter Load vs. Machine Penetration per revolution for the 30 ft. dia. Jarva TBM Operating in Chicago, Illinois.

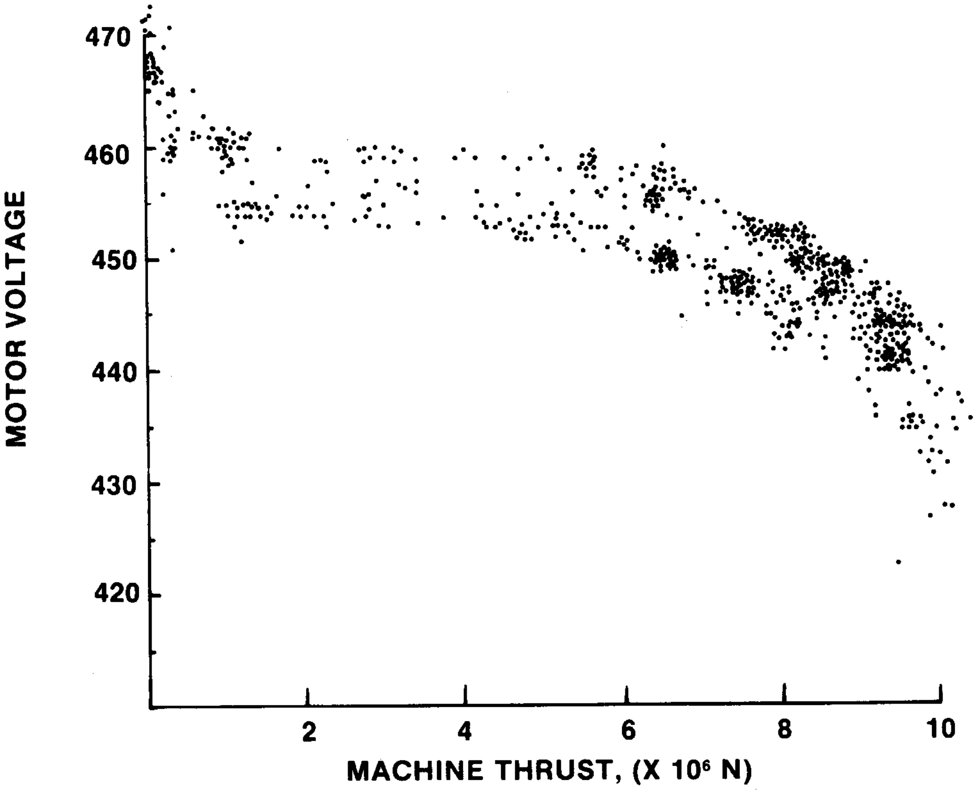

Figure 11. Machine Thrust vs. Voltage (on Drive Motor No. 11) for the 30 ft. diameter Jarva TBM in operation in Chicago, Illinois.

the statement made by the machine manufacturers that most tunnel boring machines are torque limited. Generating torque, of course, is where the machine power is consumed and adding more torque to the machine greatly increases the cost of equipment.

As noted above, the no-load torque on this particular machine appears to be around 15 to 20% of its rated torque capacity. That is, this percentage of the torque exerted on the cutterhead is actually consumed in factors other than that required for rolling the cutters, including torque required to lift the cuttings and that which is required to overcome the cutterhead friction with the tunnel walls. It would be inaccurate to conclude that a 15 to 20% no-load torque is universal to all tunnel boring machines since it is believed that this percentage will greatly vary depending on the bore size, cutterhead configuration, rock type bored, and the efficiency of the muck removal system.

The average cutter load versus the penetration per revolution relationship is shown in Figure 10. The average cutter load is determined by dividing the machine thrust by the total number of cutters employed on the machine. The penetration per revolution is calculated from the measured penetration rate by considering the cutterhead RPM. The trend observed in this graph is exactly the same as that in Figure 7 since the parameters included in these two graphs are related to each other. Nevertheless, the purpose of presenting Figure 10 was to obtain a general idea about the force levels and the resultant penetrations achieved by a machine cutter. The force exerted on a single cutter by the machine is of major significance for cutter life and more importantly for determining whether the cutter bearing capacity is ever exceeded during boring operation.

The last graph shown in Figure 11 does not carry any significance with respect to the objectives of the instrumentation, but is useful to machine manufacturers for motor design purposes. As previously mentioned, the machine manufacturer was interested in obtaining information about the drive motor voltage variation during boring and as a result, a voltage transformer was also incorporated into the instrumentation package to meet the request.

As previously noted, the data logger also incorporated alarm limits, giving an alarm when a channel of data exceeds its preprogrammed alarm value. Although not used to date, the alarm capability can prove useful in many ways for improved machine performance and life. For example, through monitoring the drive motor temperatures using thermocouples, the operator can be warned in advance of an overheating drive motor. Stresses occurring at various machine components can be monitored and an alarm is set if the stress at a particular point exceeds the value considered allowable by the manufacturer. This could potentially prevent costly machine breakdowns by providing advance warning of overstressed machine components.

Conclusions

The instrumentation program has met two basic goals. First, it has provided accurate boring data from which the interrelationships of various boring parameters were derived. Second, it has proven that despite the severe underground working conditions and the adverse environment, it was feasible to install an automatic data acquisition system incorporating sensitive electronic components on the machine. Considering the relative costs of the instrumentation system and the tunneling machine, it is not difficult to appreciate that a significant payoff exists from instrumenting a tunnel boring machine.