Instrumentation of a Reconditioned Robbins Tunnel Boring Machine – 106th Street Tunnel

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December 20, 2000

Future accelerator projects at Fermilab may require the construction of tunnels in the northern Illinois bedrock. To understand how tunnel costs might be reduced we investigate the details of conventional tunnel boring machine (TBM) operations in an on going tunnel project. This may allow us to gain insights as to how we might increase the reliability and productivity of current TBM operations. Ultimately this should lead to lower tunneling costs. We describe instrumentation that was used to measure the parameters of this TBM operation.

Project Overview

The Tunnel and Reservoir Plan (TARP) is a large complex of tunnels (about 100 miles in length) located in the Chicago area bedrock. It is used for pollution and flood control. It is the excavation of one of the tunnels in this continuing project that we instrumented.

Tunnel

The most recent addition to this system is the Torrence Avenue project, which is nearing completion. It is in Silurian Dolomite which has unconfined compressive strength which varies between 14,000 and 18,000 psi. This project consists of a single 34,150 ft long, 27 ft, 4 in diameter mainline tunnel and two smaller feeder tunnels (106th street

and 122nd street in the extreme southern part of Chicago). Each of these feeder tunnels is 17 ft, 10 in diameter and 4000 ft in length. The elevations of the three tunnels are approximately 350 ft below grade level. A reconditioned Robbins TBM was used to excavate each of these two smaller feeder tunnels. It is the instrumentation of the 106th street tunnel that we describe in this note. Figure 1 shows the penetration of the TBM from the instrumented feeder tunnel into the mainline tunnel on January 20, 2000. This dramatic entry signaled the end of the first pass of our data taking. The construction of these tunnels is a joint venture of Kenny Construction (sponsor)/Kiewit Construction/J. F. Shea.

Figure 1

TBM entering the main line tunnel

TBM

The TBM was built by the Robbins Company in 1980 with a diameter of 18 ft, 6 in and rebuilt by Kenny for the present job. It has a boring stroke of 5 ft with a thrust of 840 tons distributed on 38 cutters of 17in diameter. Six 250-hp motors power the cutter head. The machine configuration utilizes two horizontal grippers capable of a maximum gripper force of 2827 tons. The TBM weighs about 284 tons. Figure 2 is a diagram of the TBM showing the instrumentation. A horizontal conveyor belt from the cutter head to muck rail cars transports the

excavated rock. At the tunnel heading the muck cars are emptied into a hopper which is lifted to the surface by crane.

Kenny-Fermilab Collaboration Plans for TBM-Systems' Monitoring

Figure 2

TBM and monitoring system

Instrumentation

The instrumentation installed on this "vintage" TBM included temperature sensors, vibration sensors (accelerometers), hydraulic pressure sensors, electrical current sensors, and a device that measures the extension of the cutter head thrust hydraulic cylinders. Some of these devices are pictured in Figure 3. Two TV cameras (noted as observation points) were also part of the instrumentation package. We would like to emphasize that this instrumentation involved only minor modification to the TBM and it could be rapidly removed if it malfunctioned or interfered with the mining operation.

Figure 3

Sensors mounted on the TBM

Pictured (clockwise from left) are the extension sensor, current sensors, pressure indicators, and temperature sensors. Accelerometers are now shown

Data Acquisition System

The data acquisition system is shown schematically in Figure 4. The data acquisition system is housed in an aluminum environmentally protected box at the TBM heading and is shown in Figure 5. This box is mounted on the TBM trailing gear, which follows the TBM advance. Inside this box is a standard Fermilab accelerator controls system Internet Rack Monitor (IRM) module. The IRM contains a Motorola 6820 processor (the same processor that powers the Macintosh II computer). It is configured as an Internet node, and accepts and processes industry standard (Ethernet) signals from the detectors. The two TV cameras are controlled by the slow scan TV module that is also housed in the aluminum box.

Data Acquisition from TBM

Figure 4

Data Acquisition System

Figure 5

The Data Acquisition System Box interior and mounted at the TBM

The data acquisition system box (Figures 5) contains a 56K LAN modem. This allows us to transmit data over a conventional dedicated telephone line to another 56K LAN modem at Fermilab. From here one has a choice of viewing the data with the standard Fermilab accelerator control system (ACNET) or a separate Macintosh based system. Both were used.

This combination of hardware and software allows us to treat the TBM data in the same way as we would treat any other data from the Fermilab accelerator system.

All data is recorded with a time stamp (hour, minutes, seconds, date and year). Most measurements consist of a single value (temperature, current, pressure or extension) and the time stamp. This process is more complicated for the vibration sensors. Here each measurement is a matrix consisting of 1024 values of the accelerometer (each value separated by one millisecond) for each of the four accelerometers. This data is discussed in a separate section.

Figure 6 is the ACNET TBM data parameter page.

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W95 TUNNEL BORING MACHINE          SET      D/A  A/D  Com-U  *COPIES*
-<FTP>+ *SA* X-A/D X=TIME          Y=T:BAPI30,T IBEAM , ,
COMMAND ---- Eng-U I= 0          I= 0          , 0          , -5          , -2
-< 1>+ One+ AUTO F= 3600          F= 50          , 9          , 4          , 2
Z:TBMPV          Hyd. Pump Vibration          * -.029          G
Z:TBMCMV          Cutter Drv Mtr Vibration          * -.02          G
Z:TBMFV          Main Frame Vibration          * -.015          G
Z:TBMFPV          Back-up Pltfm Vibration          * -.021          G

Z:TBMTHP          Thrust Hyd Pressure          * 31.33          PSI
Z:TBMGHP          Grip Hyd Pressure          * -193.7          PSI
Z:TBMALP          Lube Oil Pressure          * -160.9          PSI

Z:TBMDOI          Drive Motor Current 0          * -.119          AMPS
Z:TBMDOI          Drive Motor Current 1          * -.119          AMPS
Z:TBMTP          Thrust Pump Current          * -.181          AMPS
Z:TBMGP          Gripper Pump Current          * -.048          AMPS

Z:TBMTP          Thrust Hyd Pump Temp          * 14.23          C
Z:TBMGP          Grip Hyd Pump Temp          * 11.83          C
Z:TBMST          Lubrication System Temp          * 17.62          C
Z:TBMCM          Cutter Drive Motor Temp          * 28.01          C
Z:TBMCE          Cutter Head Extension          * 2.078          IN

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Figure 6

The TBM ACNET data parameter page

This page lists the items that are being monitored and gives the current value of the detectors. This page can also be accessed through the WEB page. Below the four rows of page description lines, one finds four columns. The first column gives the computer name for each detector, followed by a description of the detector, then its value including units.

The first four detector lines are the vibration sensors (accelerometers). The data indicated is not relevant since it is only the first value of the above matrix. The second set of three lines is the hydraulic pressure readings for each of the three systems (thrust, gripper, and lubricating oil). The next set of four are currents in the first two drive motors (only 2 of the 6 were instrumented) and the current in the thrust and gripper hydraulic pump motors. The last group of five lines contains the temperatures for indicated motors and the extension of the thrust hydraulic cylinder.

Data Recording and Display

Data was recorded and archived to disk drives using ACNET. We recorded the signals from the detectors at 5-minute intervals. This data could be displayed using PC or Macintosh computers at Fermilab connected to the Fermilab internal network. The flexible display system in ACNET allowed one to choose a time window and display the output of up to eight devices in a single plot. Displays could also be put on Fermilab web pages, which could be viewed by anyone with password access.

Mining Cycle

Probably the most useful direct indicator of TBM performance is plotting the TBM mining cycle. To do this we plot the thrust cylinder extension (TBMCH) as a function of time. From this one plot one can easily see the progress of the TBM cutter head and compute the rock penetration rate. One can also evaluate the TBM performance by plotting along with the thrust cylinder extension pressures, currents, and temperatures. For each foot of penetration, we mine about 250 cubic feet (21 tons) of rock.

We illustrate the TBM mining cycle by displaying a series of plots over a two-hour period. In Figure 7a we plot time on the horizontal axis and the vertical axis shows the thrust cylinder extension (TBMCH) in

inches and the thrust (TBMTHP) and gripper (TBMGHP) hydraulic pressure measurements in psi (Figure 6 contains a list of these definitions). Note that the vertical scales differ for the extension and pressure measurements. Measurements were made at 5-minute intervals and in these figures the data points are connected with a straight line to guide the eye.

Referring to Figure 7a, we see (lower part of the figure) the green saw tooth display of the thrust cylinder extension. We see that this corresponds to about a 30-minute cycle, which includes the forward rock cutting motion (just under 50 inches), and the lesser time for the retraction of cylinder and the advancement of the TBM. The top part of the display shows the pressure on the thrust cylinders (about 3000 psi) and the gripper pressure and their changes during the mining cycle. Note that although the thrust cylinder was capable of a 5 ft (60 inches) extension, it never reached full extension because the muck cars were filled before that occurred.

Figure 7a

The TBM mining cycle showing pressures and thrust cylinder extension.

In Figure 7b we plot, for the same time period, the thrust cylinder extension and electrical currents in one (of six) 250 HP cutter head motors (TBMDI1), and the currents in the thrust and gripper hydraulic pumps. Again note the differences in the vertical scales. The behavior of the motors during the mining cycle is clear. Note, however, the variations in the cutter motor current during the advance period.

Figure 7b

The TBM mining cycle showing currents and thrust cylinder extension.

Figure 7c shows the measured temperatures for the same period. Included are the temperatures of the thrust, gripper, and lubricating system hydraulic pumps. The temperature of the one cutter motor that was instrumented is also shown. All are in degrees Centigrade. One sees the expected temperature behavior across the mining cycle except for the cutter motor temperature readout which was not working properly at this time.

Figure 7c

The TBM mining cycle showing temperatures and thrust cylinder extension.

Data Collection Period

Mining of the 4000-foot tunnel started near the end of October 1999 and continued until completion on January 20, 2000 (Figure 1). Instrumentation was installed and debugged simultaneously with mining. Figure 8 shows the measurements of TBMCH and TBMTPT from the period of December 6, 1999 to January 24, 2000. It is within this period that we feel that reliable data was recorded.

Let us look more closely at this plot (Figure 8). Starting from the left we see when the last instrumental modification, December 9, 1999 at about 14:00 was made. Since the temperature measurements were not working before this modification, the appearance of temperature data (TBMTPT) on Figure 8 give us a precise time marker for this modification. A few hours later we see the halting of operation because of a personal injury. At this time the temperature reaches an equilibrium point of about 12 degrees C. The next major interruption occurs for a scheduled three day Christmas shutdown starting

December 24. This is followed by a loss of data from 0:45 on December 28, 1999 to January 7, 2000 at 11:00. This corresponds to a period when the TBM power cable (and our phone cable) was being extended. The fact that there was a faulty connection to our phone line was not noticed because Fermilab was closed for this holiday period. Data taking ended with the TBM break through to the larger tunnel (Figure 1) on January 20, 2000 at 9:00. Replotting the data utilizing the much better time resolution (recall data was recorded every 5 minutes) allows one to localize these actions to a few minutes.

Figure 8

The TBM mining cycle covering the data collection period.

Penetration and Advance Rate Computations

The recorded data can be examined and used in computations. The data can be copied to a spread sheet program (like EXCEL) to yield information about the performance of the TBM. We illustrate this in Figure 9 where the plots represent the data collected in a full day (January 13, 2000). Here we plot the thrust cylinder extension (now in feet and in blue) as in the previous figures. However we can also compute the instantaneous cutter head velocity, or instantaneous penetration rate (with sign in ft/h and red).

Figure 9

One day of TBM mining.

We see (Figure 9) that when the TBM is mining rock (positive sign) it is advancing at somewhat more than 10 ft/h. The regrip cycle can proceed about 5 times faster (about 50 ft/h). With the help of the spread sheet code, we can compute the cutter head advance in the 24 hour period (131.5 ft) and thus compute the mean advance rate (5.5 ft/h) on this day. Note that it is only about one half of the best penetration rate (Figure 9) corresponding to a utilization of about 50% (3x8 hour mining) on January 13, 2000.

Let us look at the full period from the time the data acquisition system was working till the tunnel completion. Figure 8 shows us that

this is the period from December 9, 1999 (14:00) to January 20, 2000 (9:00). If we exclude from this period the time of the faulty telephone connection (December 28, 1999 (0:45) to January 7, 2000 11:00) we find that 1971 ft of tunnel were mined in 704 hours or a mean tunneling rate of 2.81 ft/h. Correction is not made for the time tunneling operations were suspended for the Christmas holiday.

INTERNET Plots

As the run progressed the on-line plots became available. They could be accessed on the INTERNET through a Fermilab web page:

<http://www-linac.fnal.gov/cgi-bin/tbm.pl>

At that point you will be asked for the user name and password:

kfjointproject
17ftTBM106St

The first page is shown in Figure 10. It shows two television cameras that were mounted on the TBM trailing gear. The first camera was directed at the conveyor belt and could be used for monitoring the quality (size and shape) of the excavated rock. The second camera was directed at the tunnel ceiling and could be used to monitor the tunnel rock for intersecting fractures-potential zones of instability, etc. For each camera a frame was recorded every minute and 30 frames spooled. This allowed a 30 frame movie to be replayed under user command for each camera. Lighting conditions were not always optimal (as in Figure 10) but this should not be an intrinsic problem.

Figure 10

First On-line page

Two plots were also available on line. Tunneling progress for the last day (24 hours) shown as Figure 11. Here was plotted as a function of time the thrust cylinder extension and the thrust pump temperature. From these one could get the status of the mining operation. Another plot (similar to Figure 8) was available with data from the last week. These plots were remade every hour and put on the Internet page. Thus an hourly report was available to anyone who had the interest (and password) to access them. The one-hour update could certainly be made shorter. Anyone who had direct access to the Fermilab system could make any displays they wished as soon as the data was taken.

Figure 11

24 hour On-line page

Vibration Sensors

Data collection is more complicated for the vibration sensors. Here each measurement is a matrix consisting of 1024 values of the accelerometer (each value separated by one millisecond) for each of the four accelerometers (Figure 6).

The data from each of these accelerometers is 1024 measured values of the force (proportional to the acceleration) on the sensor and this is plotted in Figure 12. This “time domain” plot displays the amplitude of the displacement as a function of time.

Figure 12

Time Domain Spectra

Using a Fourier transformation, the time domain information can be converted to the “frequency domain”. Figure 13 shows the data of Figure 12 after the transformation. In it we display the frequency spectra, the amplitude as a function of frequency. Note the peak at the 60 Hz line voltage.

Figure 13

Frequency Domain Spectra

Although the ability to make these measurements was clearly demonstrated, software was not readily available to record them. Thus they could not be systematically studied at a later time and correlated with TBM failures.

Important questions, which still need to be studied, include. What is the important frequency range? How does one use this to predict failures?

What have we learned?

1. Monitoring the operation of a reconditioned TBM can be done relatively easily. Instrumentation can be attached to the TBM using few “hard” connections and without interfering with production. The logged data provides all the information needed to assess the progress and status of a TBM system.
2. The status of the tunneling operation can be posted in real time on the Web where it is available (underpass word control).
3. Data could be made available to make rapid decisions (time = \$).
4. How do we best use all of the information?
5. How can we identify potential failure points?
6. How would we use the accelerometer data?
7. Can this data be use to for preventative replacement/maintenance?
8. Can we identify causes for reoccurring downtime in real time.
9. Data can provide for comprehensive review without going underground.
10. This was a bi-directional data system. It was used only to monitor the TBM performance. Control functions could also be initiated operations. Is this useful?