Monitoring Earth Pressure Balance Tunnels in Los Angeles

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ABSTRACT: Tunneling using earth pressure balance (EPB) tunneling methods has been active in Los Angeles over the last seven years. Three recent large-diameter EPB tunnel projects have been completed to create approximately 32km (20 miles) of pre-cast concrete lined tunnel excavated through alluvial soils and soft, sedimentary rock. This paper addresses monitoring of ground surface subsidence using data collected from geotechnical instrumentation and TBM performance parameters. TBM operating data are used in conjunction with surface-installed instrumentation to predict surface subsidence. TBM operations may then be adjusted to reduce potential settlement-related damage to adjacent structures or utilities. Monitoring instruments using remote access is also addressed. The paper provides case histories of successful performance monitoring to support future urban tunneling projects.

1. INTRODUCTION

More than 80 km (50 mi) of large diameter tunnels have been constructed in Los Angeles, California (USA) over the past 20 years. Three recent projects are the East Central Interceptor Sewer (ECIS) and Northeast Interceptor Sewer (NEIS), owned by the City of Los Angeles, and the most recently completed tunnels for the Metropolitan Transportation Authority's (Metro) Gold Line Eastside Extension tunnels for light rail (MGLEE). Minimizing ground surface settlement was of paramount importance for all of these urban tunnel projects. Pressure Face TBMs, i.e., Earth Pressure Balance (EPB) or Slurry Machines, were specified for these projects to reduce subsidence risk. For all three projects, the contractors selected EPB TBMs.

The ECIS project (Figure 1), completed in 2004, involved over 18 km (11mi) of EPB tunnel using four TBMs (Crow and Holzhauser, 2003). The NEIS project was completed in 2005 and included 11 km (7 mi) of sewer tunnel (Zernich et. al., 2005), The MGLEE tunnels, completed in 2006, comprised 2.2 km (1.3 mi) of twin bore tunnels, using two EPB TBMs. All of these projects were located in a densely populated urban area (Choueiry et. al. 2007).

FIG 1. Location of Metro and Major Sewer Tunnels, Los Angeles

All three tunnel projects demonstrated successful tunneling performance in terms of surface settlement, although there were occasional incidents of surface settlement greater than allowable along the ECIS alignment. These occasional incidents were successfully mitigated.

The NEIS tunnels were bored considerably deeper than the ECIS tunnels, were of smaller diameter, i. e., 3.7 m (12 ft) for NEIS vs. 4.72(15.5 ft) for ECIS, and were located below the water table. These circumstances, which were more forgiving on the one hand, required more diligent application of EPB practice on the other. Nonetheless, the experiences on both ECIS and NEIS provided meaningful lessons for future tunnel work. Lessons learned were incorporated into the MGLEE project, which was highly successful in terms of avoiding measurable surface settlement.

1.1 Reducing Surface Subsidence

Surface settlement, or ground subsidence due to tunneling, can cause damage to roads, utilities, buildings and other structures. Tunneling experience in Los Angeles using open shield methods demonstrated such potential during previous tunnel projects. The risk potential was therefore heightened for the subject projects, and this led to the specification of pressure-face TBMs. The closed and pressurized face reduces loss of ground at the tunnel face and, when the machines are used in combination with gasketed pre-cast tunnel liners and backfill grout behind the installed segments, losses from over-cut of the excavated surface are also reduced.

Identifying and mitigating subsidence were identified as major objectives in the development of the MGLEE project. A key element to this strategy was the incorporation of lessons learned on the ECIS and NEIS tunnels. The design for MGLEE thus incorporated several measures beyond the requirement for ECIS and NEIS with respect to pressure face TBMs for subsidence mitigation. These included: ground modification using permeation and compensation grouting in some cases, and adjustment of TBM operations in others. The principle of compensation grouting involves carefully controlled injection of grout between the tunnel crown and surface above during tunneling, allowing raising of the structure should settlement occur. These adjustments included modifications to applied face pressure and backfill grout volumes. Identifying ground surface settlement, achieved through extensive surface survey and instrumentation was key to assessing performance.

Settlement mitigation through compensation grouting during tunneling was not required for MGLEE. This was attributed to the Contractor conscientiously following good EPB tunneling practice, as well as ground conditions that appeared to be ideal for EPB tunneling. Relatively little measurable surface settlement occurred, the average being 0.25 cm (0.1 in.) and the maximum being 12.2 mm (0.48 in) in over 2.1 km (1.3 mi) of tunnel. Nonetheless, continuous monitoring of machine performance and surface settlement was necessary throughout the project so that if action thresholds, as defined in the specification, were reached, appropriate mitigation measures could be taken.

The sections below describe the instrumentation and surveying methods used to identify surface settlement on the three projects. This is followed by a discussion of TBM data used to assess performance as it evolved on the MGLEE project.

2. INSTRUMENTATION MONITORING PROGRAM

2.1 Organization

The instrumentation and monitoring responsibilities for the ECIS, NEIS, and MGLEE projects were structured similarly. The types of instrumentation were indicated on the project plans and specifications. Furnishing, installing and maintaining this equipment was the responsibility of the Contractor, while data collection and management and reporting were the responsibility of the Owner’s Construction Manager (CM). Such organization allowed the Contractor to schedule and integrate instrumentation installation with other construction activities to limit construction conflicts and damage to installed equipment as well as limiting public inconveniences such as lane closures for multiple construction activities. Additionally, the Owner had the convenience of collecting data as often as desired without waiting for the Contractor to provide readings. Managing the databases also gave the Owner the flexibility to process and provide appropriate data presentation to all interested parties in a timely manner.

2.2 Instrumentation

The contracts for the three projects specified action level and maximum allowable surface settlements. The specifications also prescribed maximum downward movement of soil directly above the tunnel crown, which eliminated tunnel depth considerations from performance analysis.

The eight EPB tunnel reaches were monitored using several types of instrumentation including: multiple point borehole extensometers (MPBXs) as well as conventional survey of surface settlement points. Braced station excavations (not addressed in this paper) were monitored using inclinometers, observation wells with strain gauges placed on struts.

Tunneling generally occurred below public right of way (city streets). Arrays of MPBXs, along with surface settlement survey points, were placed at cross streets to identify the surface settlement trough characteristics. Figure 2 illustrates a typical instrumentation layout and cross section for the MGLEE twin bores.

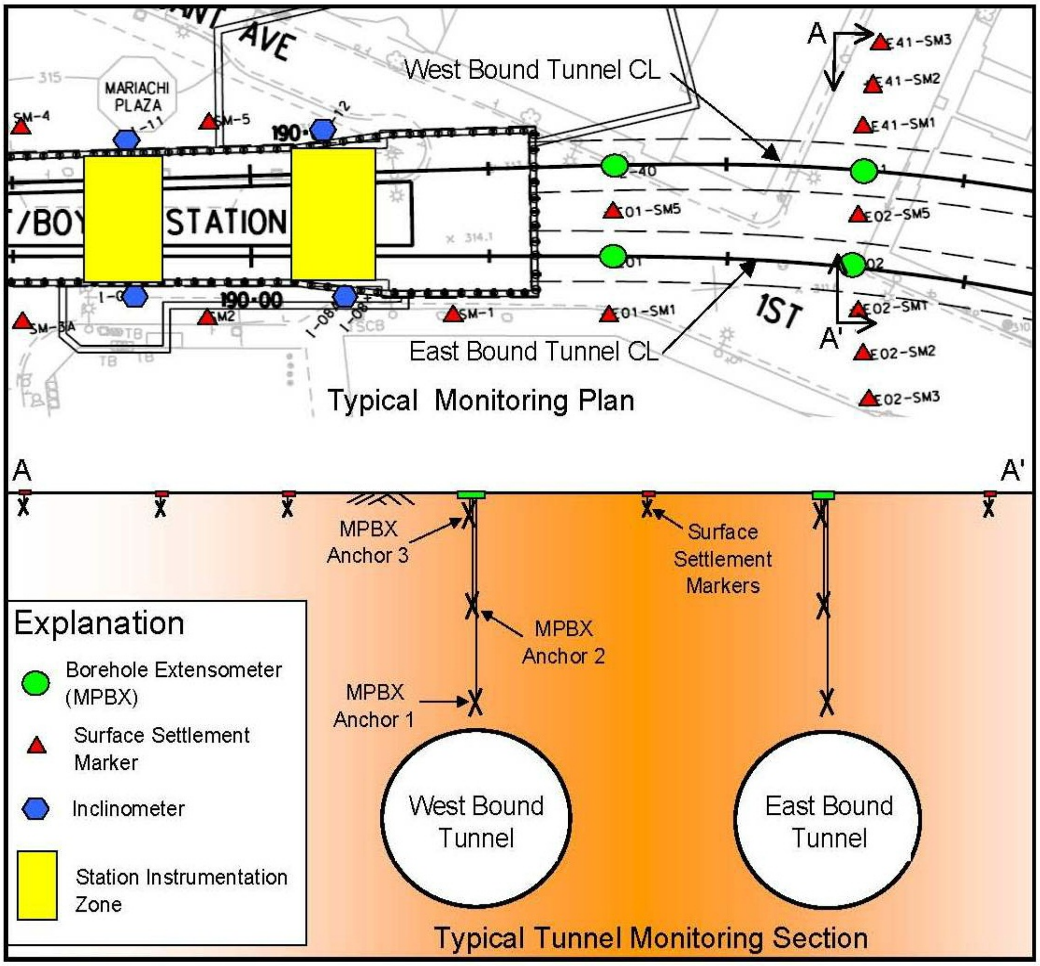


FIG 2. Typical Instrumentation Layout above MGLEE Tunnels

MPBXs were spaced as close as 15 m (49 ft) along the alignment at critical locations, and as much as 75 m (250 ft) along less critical areas. Lower anchors were installed approximately 1.5 m (5 ft) above the proposed tunnel crown, surface anchors were set 1.5 m (5 ft) below the ground surface and the middle anchors were spaced equidistantly between the upper and lower anchors (Fig 2).

The three projects used approximately 360 MPBXs and thousands of surface settlement points, with the majority of these extensometers and survey points located within traffic lanes of heavily traveled city streets. With the large amount of available data provided by the TBM (discussed further below) it was important to have enough subsurface and surface settlement readings to accurately analyze the tunneling performance during excavation. Tightly spaced MPBXs at the start of each tunnel drive were valuable to correlate settlement with TBM performance.

Data collection

Data collection posed one of the biggest challenges of the tunnel monitoring program. At times monitoring included collecting data for four active tunnel headings in addition to simultaneous shaft excavations. Electronic data collection from MPBXs evolved from hand held storage devices, to two-way radio transmission, and finally to cellular modem transmission. In addition to MPBXs and surface surveys, the tunnel monitoring included an Automatic Data Acquisition system installed in the TBMs. Along with survey data, all information data could be reviewed, processed, summarized and distributed within a few hours. For MGLEE, however, this process could be completed within a few minutes of the data readings for critical locations. Additionally, real time data from the extensometers could be monitored at the MGLEE project field office via cellular modem, whereas on previous projects real time data could only be viewed in the field.

This data was processed for graphic presentation to quickly assess settlement and TBM performance. Graphs, as shown in Fig 3, were prepared to show MPBX data with respect to TBM position.

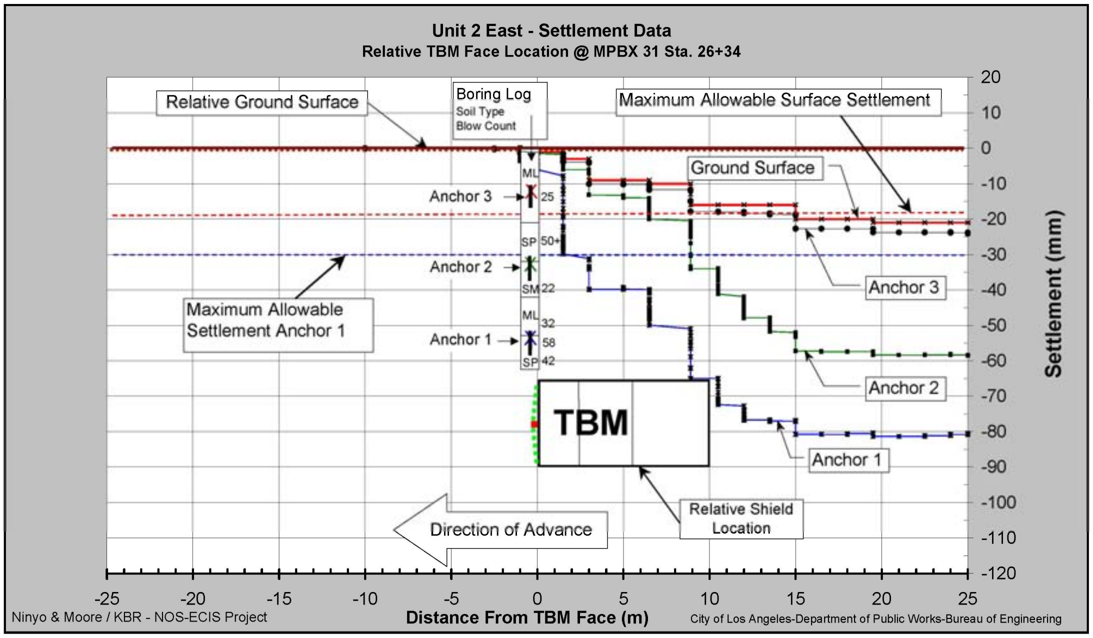


FIG 3. Data presentation for MPBX on ECIS Project

During the ECIS and NEIS projects, the initial procedure to collect the MPBX data required the technician to control traffic, remove instrument traffic covers, and then download information from a data logger, often while standing in the middle of the street. This entailed up to 30 minutes and often involved traffic lane closures.

Performing such operations for four tunnel drives spread over 18 km (11 miles) of alignment involved several hours, and thus created a lag in the timely identification of excessive settlement. This system was upgraded considerably using a two-way communication device and laptop computers with the ability to transfer data via an attached cellular phone. This allowed the technician to safely stand on the side of the road, connect to the data logger using two-way communication and download or program the data logger as needed. The data was then sent to the office server with the cellular phone modem and processed within minutes of the last reading. At times, there was some difficulty with transmission through the traffic covers and passing cars, but several antenna options, including a large hand held antenna, as well as the perseverance of the technicians, contributed to a successful field operation.

The MGLEE project provided the opportunity to further upgrade MPBX data collection techniques. The MPBXs were similar to those on the ECIS and NEIS projects and were also located within high volume traffic corridors. The data loggers for the MGLEE project were, however, equipped with cellular modems in an attempt to collect data from almost any location and at any time. Based on the experiences of ECIS and NEIS, transmitting through the traffic covers would pose the greatest difficulty. The solution called for testing the first MPBX installation by simply putting a cell phone in the traffic cover and testing for phone reception.

Field testing of a data logger prototype resulted in less success than the cellular phone method, and required retrofitting the data logger with an external antenna and a cable extension. The retrofit involved placing small holes in the traffic covers that allowed portions of the antennas to be exposed. This adaptation was sufficiently successful to use the remaining data loggers with this configuration. Ultimately antennas were mounted on top of the traffic covers and reception was greatly improved. Antennas, however, were exposed to damage and suffered a high mortality rate.

After limited success with customizing traffic covers and replacing damaged antennas, the team did not consistently use the cellular modems. In many cases, cellular reception was poor along portions of the alignment. The relatively short alignment allowed quick access to all locations, along with contract provisions that enabled the Contractor to provide traffic control, this meant that rapid recovery of data was still possible.

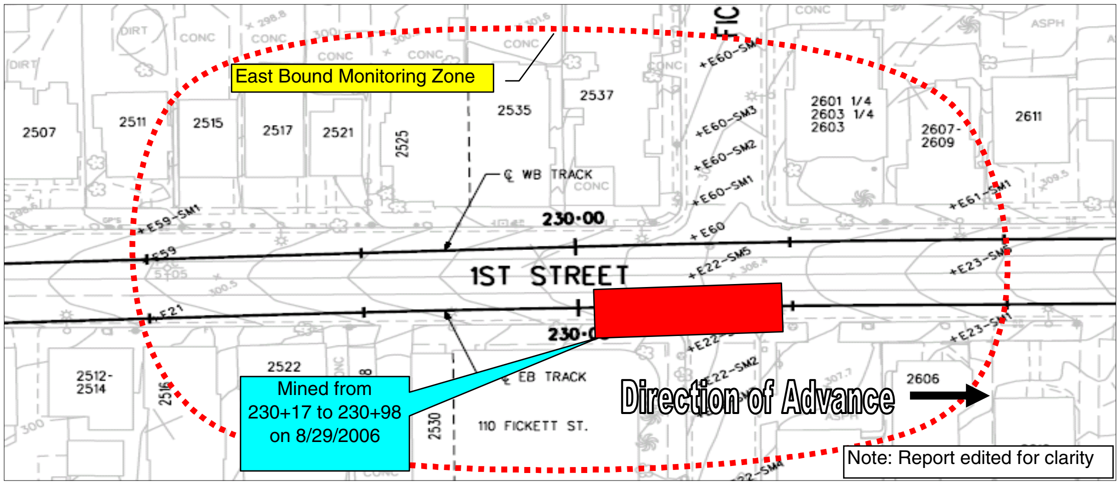
The majority of the data from extensometers were collected using a laptop computer with hard wire to the MPBX data logger in the field. This allowed the technician to determine in the field if action levels had been reached. The technician would then bring the data to the field office for further formatting, analysis, and dissemination.

2.2.2 Monitoring Frequency

Tunneling on the ECIS and NEIS projects was for the most part under wide city streets, entailing single bores and smaller diameters. MGLEE on the other hand, entailed two larger bores with the alignment along a narrower street and closer to, or directly beneath, surface structures. Tighter control was thereby required for MGLEE. The comprehensive surface monitoring program for MGLEE was accomplished by MPBX monitoring with over 1,500 survey points along the alignment and using differential leveling survey techniques to record the elevations throughout the tunneling phase.

EastBound: Surface Settlement Monitoring

Station	Offset		8/22/06	8/23/06	8/24/06	8/24/06	8/25/06	8/25/06	8/28/06	8/29/06
228+00	0		0.02 in	0.07 in	-0.02 in	0.06 in	0.02 in	0.05 in	0.08 in	0.01 in
228+11	17	R	0.02 in	0.11 in	-0.02 in	0.07 in	0.01 in	0.05 in	0.08 in	0.00 in
228+25	0		0.01 in	0.07 in	-0.02 in	0.07 in	0.04 in	0.04 in	0.07 in	0.02 in
228+31	17	R	0.01 in	0.11 in	0.02 in	0.12 in	0.07 in	0.06 in	0.11 in	0.10 in
228+40	17	R	0.02 in	0.01 in	-0.04 in	0.07 in	0.02 in	0.04 in	0.11 in	0.02 in
228+50	0		-0.04 in	0.05 in	-0.05 in	0.05 in	0.01 in	0.02 in	0.05 in	-0.01 in
228+61	17	R		0.11 in	-0.05 in	0.11 in	-0.04 in	0.02 in	0.13 in	-0.07 in
228+75	0			0.07 in	-0.07 in	0.06 in	0.00 in	0.02 in	0.07 in	-0.01 in
228+82	17	R		0.12 in	-0.06 in		-0.06 in	0.01 in	0.00 in	-0.06 in
228+92	20	R		0.08 in	-0.10 in	0.07 in	0.00 in	0.04 in	0.17 in	-0.06 in
229+00	0			0.08 in	-0.10 in	0.08 in	-0.02 in	0.01 in	0.07 in	-0.05 in
229+05	20	R		-0.14 in	-0.05 in		0.02 in	0.01 in	0.11 in	-0.08 in
229+50	0			-0.01 in		0.01 in	-0.07 in	-0.07 in	-0.01 in	-0.11 in
230+50	0								0.04 in	-0.06 in
230+75	0								0.04 in	-0.05 in
231+00	0									-0.02 in



East Bound Monitoring Zone

Mined from 230+17 to 230+98 on 8/29/2006

Direction of Advance

Note: Report edited for clarity

FIG 4. Format, Surface Settlement Data Daily Report

The crews performed leveling surveys during each shift of tunneling. Each survey run began approximately 30 m (100 ft) in advance of the TBM and extended to approximately 100 m (300 ft) behind the TBM. The survey included tunnel centerline measurements every 8 m (25 ft), as well as buildings within 100 ft of the centerline. . Additionally, the survey included arrays of points orthogonal to the centerline, which occurred every 30 m (100 ft) and extended out as far as 40 m (140 ft) from the centerlines, generally at street intersections. Points adjacent to the extensometers were included in the conventional surveys and used to correct relative movement of the MPBX anchors. The data collected were evaluated and distributed in a daily report. Reports consolidated data to provide a clear picture of the TBM position and surface settlement at specific locations and times. Figure 4 reproduces a portion of a daily report format.

3. TBM PERFORMANCE MONITORING

Prior to pressure-face tunneling, monitoring of ground loss from the tunnel excavation was limited to visual observations and counting muck cars. Monitoring of ground surface with MPBX and leveling has also been used effectively for many years. These measures, however, give no indication of the cause of settlement. Additionally, since MPBX measurements are widely spaced and surveying occurs after the fact, MPBXs may not be comprehensive predictors of imminent settlement. EPB technology affords parameters that can be used to assess ground loss potential, which in turn indicate the likelihood of surface settlement. The parameters are the earth pressure measured in the TBM plenum and the amount of grout injected into the annular space between the excavated surface and structural lining. The next section discusses these parameters and the associated phenomena.

3.1 Stability of the Tunnel Face

Tunneling technologies have evolved over the past 20 years to limit the amount of ground loss (over-excavation) through better control of the tunnel face and excavated perimeter. Pressure-face TBMs, as used on the three projects described herein, demonstrate an important, cost effective approach to limiting over-excavation. The principal of EPB is straight forward, i.e., the pressure exerted on the working face is sufficient to prevent unexcavated soil and groundwater from running or flowing into the tunnel. To accomplish this, EPB technology incorporates a chamber, or plenum, at the working face that is sealed from the tunnel environment. Excavated soil fills the chamber and is removed from the chamber via an enclosed screw conveyor and discharged at the end of the screw through a gate. Once the plenum and screw are filled, pressure builds up and is controlled by the advance rate of the machine and discharge rate through the auger. A schematic cross section of an EPB TBM is shown in Fig. 5.

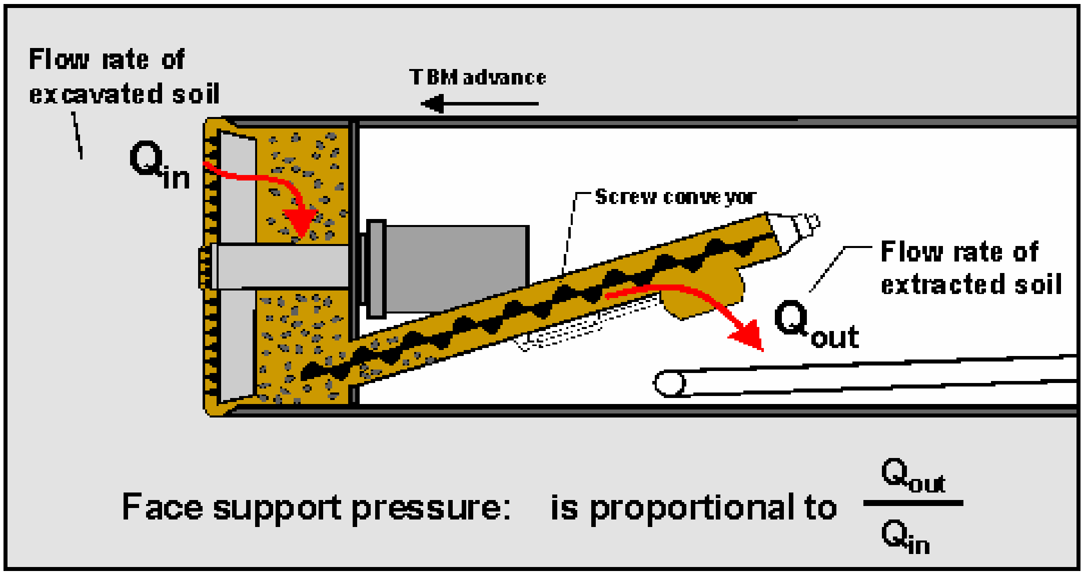


Figure 5 Schematic of EPB TBM

When balanced, the closed system exhibits steady-state condition, such that:

$Q_{in} = Q_{out}$, in which
Q_{in} = soil "flow" into the system and
Q_{out} = "flow" out of the system.

Under steady-state conditions constant pressure in the plenum and screw auger preclude over-excavation. The pressure maintained in the plenum and screw auger is the most important parameter. Low pressure indicates that steady-state flow is not present in the system or the chamber is not full, the working face may not be stable, and over-excavation could occur.

For the MGLEE operation, the contractor computed the required pressure in the plenum. The specifications required this to be equal to the hydrostatic pressure plus the soil pressure, with soil pressure estimated to be between 10 psi and the at-rest horizontal earth pressure. As an applied safety factor, the contractor added 0.3 to 0.8 bar (4 to12 psi) above the theoretical pressures. These pressures were computed over the entire alignment for the varying water and soil pressures that the TBM would encounter. The computed pressures provided guidance to the TBM operators concerning the pressure to be maintained upon the tunnel face at any point along the alignment.

Because the pressure within the plenum is such an important parameter in maintaining the stability of the working face, each TBM had six pressure gauges installed in the bulkhead wall of the plenum. These were located at various levels as pressure varies from top to bottom of the plenum and wear could possibly render them ineffective. Pressure cells were constantly monitored and were re-calibrated monthly.

3.2 TBM Data Acquisition

Each TBM transmitted real-time data to project field offices. The data transmitted included over 100 parameters, recorded every 10 seconds. This resulted in 864,000 elements of data for each machine daily. Although all of the parameters were pertinent to TBM operation, parameters such as soil pressure in the plenum and grout quantities were of paramount importance with respect to the stability of the face and subsequent subsidence. Other parameters include extension of hydraulic rams, segment erecter position and grout volumes injected. In "real time" TBM parameters were transmitted to the Contractor and CM's field offices. They could therefore assess progress and TBM performance instantly.

A rapid determination was made regarding the adequacy of the earth pressure in the plenum by a graphical analysis of the data. Several MS Excel macros were developed to assist in manipulating the extensive amount of data and portray a summary of the desired information. Figure 6 shows the graphical output for this analysis. The graph shows the upper and lower bounds of the desired pressure and the instantaneous readings of the top pressure cell (#1 cell) as well as the average of all 6 cells. For frame of reference, the graph also shows the TBM cutting edge station at a given time. The average cell pressure over the entire 24-hour span is also shown.

The graph shows the pressure in cell #1 to be low, however the plot of the average of all six cells, shows that the pressure throughout the plenum is more than adequate. This indicated malfunctioning of this cell. Pressure cells could be installed and removed from within the TBM ("back-loaded") without man entry into the plenum, and when malfunctioning occurred, a cell could be easily replaced. In this case, the cell was caked with clay so it was cleaned, calibrated, and re-installed.

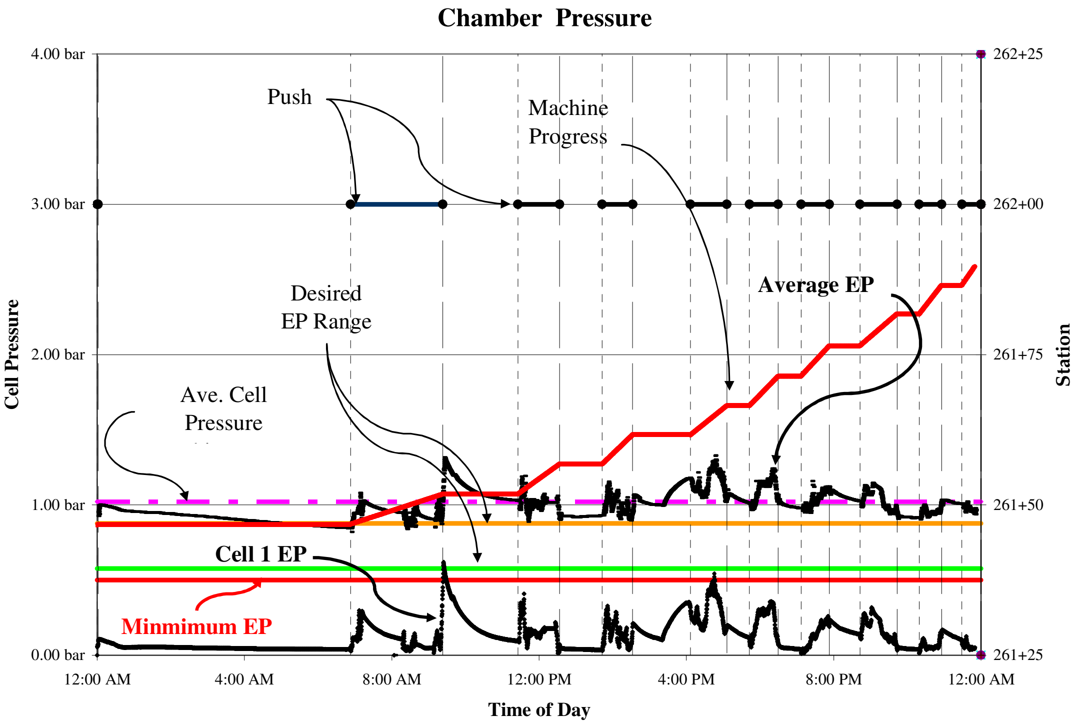


Fig 6: Graphic Daily Summary of Earth Pressure

Filling the Annulus

In addition to ground loss occurring at the working face, another source of loss is within the annulus formed between the excavated perimeter surface and the outside of the installed lining. For MGLEE tunnels, the additional "gap" was 135 mm (5.32 in). This gap could potentially result in void space into which soil can collapse, so the void is filled with grout. To accomplish this, grout ports were located at the extreme end of the TBM shield. The theoretical volume of the annulus for a 1.5 m (5 ft) tunnel segment was 4,146 liters (5.42 cy).

To monitor ground loss via the excavated annulus, backfill grout take volume, which was one of the components of the automated data acquisition, were analyzed daily or more frequently as required to understand performance.

Table A below illustrates the following parameters: TBM advance or "push" sequence for a 24 hour period; the installed ring number; the time that the push started and stopped (24-hour clock); the TBM stationing of the start and stop of the push; the grout take; and the theoretical potential for lost volume of ground (ground loss). The last column contains a "conditional formatting" command, which showed red numbers when values greater than 0.5 percent occur. These values were flagged because the project was predicated upon a maximum ground loss of 1.0 percent, and 0.5 percent would indicate an "action" level. Exceeding the action level value triggered further in-depth investigation.

Table A: Example Daily Backfill Grout Data

Push	Ring#	Start	Stop	Station From	Station To	Grout Take (CY)	Est. Theoretical Lost Volume (%)
1	1,341	0:00:06	0:01:26	261+47	261+47	5.26	0.01
2	1,342	6:53:05	9:23:00	261+47	261+52	5.40	0.03
3	1,343	11:25:42	12:33:20	261+52	261+57	6.54	-1.65
4	1,344	13:42:47	14:32:31	261+57	261+62	7.19	-2.57
5	1,345	16:06:30	17:05:36	261+62	261+66	5.25	0.25
6	1,346	17:42:39	18:29:33	261+66	261+71	5.15	0.40
7	1,347	19:06:57	19:52:51	261+71	261+76	5.37	0.08
8	1,348	20:42:46	21:43:11	261+76	261+82	5.51	-0.14
9	1,349	22:19:15	22:55:38	261+82	261+87	5.67	-0.36
10	1,350	23:28:41	23:59:54	261+87	261+91	2.81	3.59

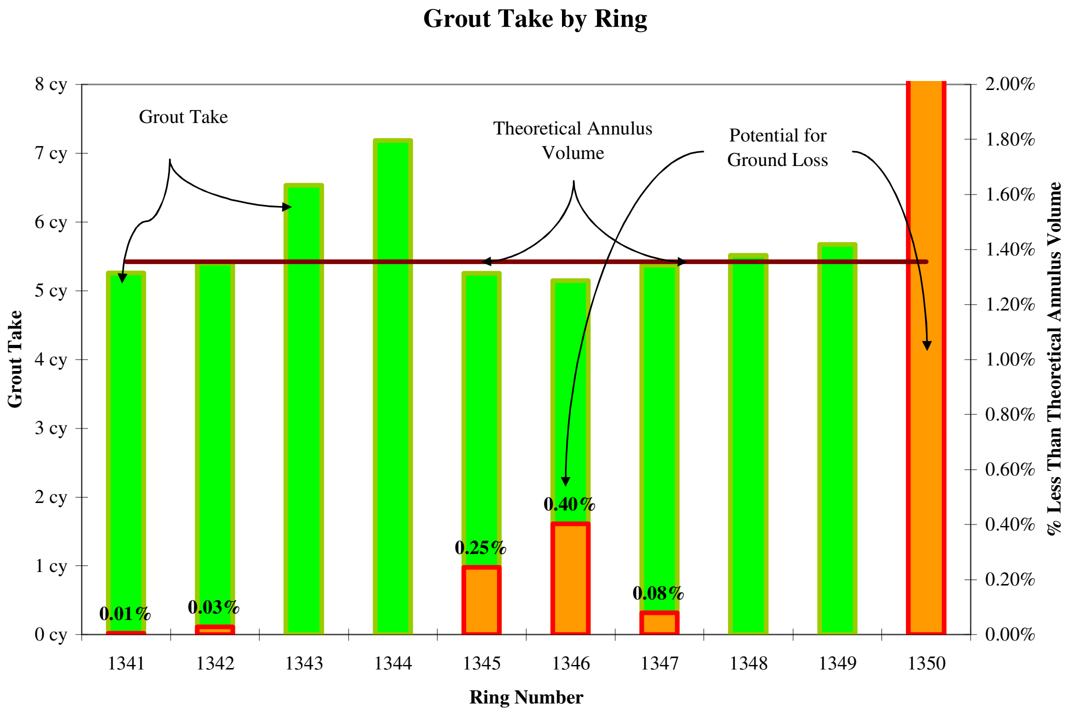


Fig 7: Graphic Display of Backfill Grout Quantities

Graphical output was also generated, as shown in Figure 7. In this example, push No. 10 would be taking place at the end of one day and into the next day. Data acquisition for that day, however, ended at 11:59:59 PM. This required that the final grout take quantity be determined at the completion of that push, which was recorded as data for the next day. Thus, the high apparent high readings do not necessarily indicate excessive ground loss. Since the data were readily available due to the contemporaneous data acquisition scheme, it was a relatively simple matter to make the necessary adjustments to correct for this. The Contractor and CM team could correlate proper earth pressure within the plenum and sufficient grouting of the annulus to limit the potential for settlement

CONCLUSIONS

Monitoring data– geotechnical instrumentation and TBM performance - were for the most part automated and could be retrieved in real time or within a few hours. This allowed for the TBM data to be analyzed in conjunction with the geotechnical data within minutes of collection. The result was a timely cause and effect analyses of TBM performance, which was essential to verifying compliance with the tunneling specifications and to initiating mitigation plans in a timely manner. This experience proved invaluable, since geotechnical instrumentation can only be installed at discrete points. With subsidence related to TBM performance, the stream of TBM data not only provided a continuous record of performance, but also afforded a means to indicate potential subsidence. Conventional surveying verified the predictions.

The ability to monitor tunneling performance using the real time TBM performance data while verifying these results with traditional geotechnical monitoring and surveying, provided further evidence that EPB TBMs can safely excavate in an urban setting with limited cover through soft and dense alluvial soils. The data produced will provide case histories of successful performance needed to support future projects.

As technology advances, automated systems have the potential to reduce the number of technicians needed to read instrumentation. For example using data loggers with cellular modems from within traffic covers has already shown promising results and can facilitate web based data management from remote locations. Addition testing of more durable antennas, signal boosters, and traffic cover composition is needed to provide more reliable results

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