Utilization of Strain Measurements on Shielded Tunnel Boring Machines

Brad Murray
Jacobs Associates, Pasadena, California

John Waggoner
GeoPentech, Santa Ana, California

Sam Swartz
Jacobs Associates, Seattle, Washington

Howard Lum
Metropolitan Water District of Southern California, Los Angeles, California

ABSTRACT: Evaluating the performance of a shielded tunnel boring machine (TBM) can be difficult because the ground cannot be observed directly and in relation to the TBM attitude within the excavation. It is difficult to determine whether performance problems are caused by ground loading, steering issues, fine muck packing against the shield, or migration of annular grout around the shield. The Arrowhead Tunnels Project in Southern California uses strain gauges on its shielded hard rock TBMs to detect shield strains early and correlate them with tunneling conditions, thereby increasing the chances that problems will be correctly diagnosed and addressed to optimize TBM performance. The frequent automatic measurement of shield strain has also been valuable by confirming whether remedial methods used to free the machine after stoppages are effective. This paper discusses the qualitative interpretation of characteristic strain patterns on the Arrowhead Tunnels TBM shields and discusses installation details and special considerations for setting up a strain measurement system.

INTRODUCTION

Various loading conditions on a tunnel boring machine (TBM) shield can contribute to significant delays during excavation due to the binding of the shield against the ground. Loads can develop from a number of sources, including global or local ground loads, TBM propulsion-induced loads, grouting-induced loads, and groundwater pressure (although groundwater pressure is not a source of shield binding). When a TBM doesn't advance as expected, it is sometimes difficult to know which load sources are responsible for the delays. If increasing shield loads can be detected early, this information can be used to gain a better understanding of conditions and adjust excavation techniques to optimize TBM performance.

Strain gauges have been used for numerous engineering applications to detect loads on structural members. They are often mounted onto steel struts and braces used for excavation support, onto steel rebar in reinforced concrete, and onto welded steel pipes placed in pressure tunnels. Strain gauges can be mounted to the inside surface of the shield on a shielded TBM (which is actually a thick-walled welded steel pipe) to detect loads on the shield. Frequent and consistent monitoring of strain gauges within the TBM shield shows the relative magnitudes and patterns of loads acting on the shield. By continuously monitoring shield strains, valuable insights can be gained when the timing of the shield deformation is correlated to specific ground conditions and construction activities.

For the Arrowhead Tunnels Project in San Bernardino, California, strain gauges installed on the shielded TBM provided data that was used to evaluate the interaction between the shield, the ground, and the construction means and methods. This paper presents characteristic loading patterns observed on the Arrowhead Tunnels Project and discusses practical requirements and considerations for implementing a shielded TBM strain monitoring program.

ARROWHEAD TUNNELS PROJECT BACKGROUND

The Arrowhead Tunnels Project is a component of the Inland Feeder Program which is part of Metropolitan Water District (MWD) of Southern California's Capital Investment Programs. These programs will increase MWD's water delivery capability to Southern California. The Inland Feeder spans approximately 71 km (44 miles) from the San Bernardino Mountains above the city of San Bernardino

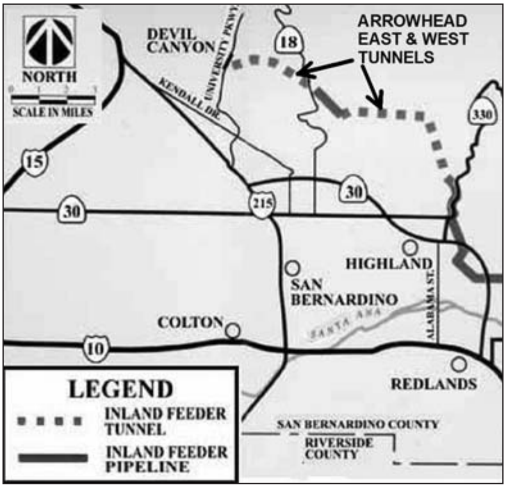


Figure 1. Location of the Arrowhead Tunnels in San Bernardino, California

to the San Jacinto Valley in Riverside County. It consists of 31 km (19 miles) of tunnel and 40 km (25 miles) of cut-and-cover pipeline. The finished inside diameter of the conveyance pipeline is 3.7 m (12 ft), and it has a capacity of 28.3 cubic meters per second (1,000 cubic feet per second). The Arrowhead West Tunnel is the first leg of the project, consisting of a 6.4 km (4 m) long tunnel that travels southeast through the San Bernardino Mountains from the Devil Canyon Power Plant to Waterman Canyon near Highway 18. After a 1.22 km pipeline segment under Waterman Canyon, the Arrowhead East Tunnel continues southeast for about 9.7 km (6 m), reaching depths of more than 610 m (2,000 ft) below the ground surface and exiting at City Creek Canyon. The finished project will connect the California Aqueduct of the State Water Project from Northern California to Southern California. A general project map is shown in Figure 1.

Construction began on the Arrowhead East Tunnel in early 1997. After mining of about 2.44 km (1.5 m) of this tunnel from City Creek Portal site, construction was halted due to elevated groundwater inflows into the tunnel. The Arrowhead West and East Tunnels were redesigned in 2000 to incorporate a new bolted and gasketed primary support system. The contract was awarded to Shea-Kenny Joint Venture in 2002. The projected construction completion date is 2010.

The tunnel alignments are located along the southern front of the San Bernardino Mountains, about 1 km (0.6 miles) northeast of the San Andreas fault zone. Tunneling conditions in the area are very challenging: the alignments are in close proximity to a tectonic plate boundary, ground cover is up to 600 m (2000 feet), and groundwater head is about 275 m (900 feet), which can cause high groundwater inflows and local zones of unstable or flowing ground. Concerns about significant tunneling-related impacts to groundwater and surface water resources dictated the use of a relatively watertight primary lining system and compatible excavation method. Fully shielded, hybrid rock TBMs were developed by Herrneknecht to excavate both tunnels and install bolted and gasketed concrete segmental liners. The hybrid nature of these rock TBMs comes from their ability to seal out 3 bars (44 psi) of groundwater pressure at the cutterhead bearing seal during operation and 10 bar (147 psi) in static mode.

Despite modifications to increase the TBM thrust capacity from the manufactured limit of 27,270 kN (6.6 million lbf) to 54,540 kN (13 million lbf), and the ability to utilize an additional 54,500 kN (12 million lbf) from 11 auxiliary jacks, both TBMs experience occasional stoppages which contribute to expensive delays. To better understand the causes of the stoppages and perhaps prevent them from occurring, vibrating wire strain gauges were installed on the inside of the shields.

The TBM shield is composed of a front shield, middle shield, and fully articulated tail skin. Table 1 lists the basic dimensions of the Arrowhead Tunnels shields. Five strain gauges were affixed to the upper half of the front shield, approximately 2.5 m (8 ft) behind the cutterhead, and three strain gauges were affixed to the upper half of the tail skin, approximately 10 m (30 ft) behind the cutterhead. Both TBMs were instrumented similarly. The position of the gauges around the shields is shown in Figure 2. Each gauge is designated by clock position in the strain-time history plots that follow.

SHIELD STRAIN AND IDEALIZED STRAIN PATTERNS

The strain gauges on the Arrowhead TBMs detect unidirectional length changes over a span of a few centimeters on the intrados of the shield. Depending on the nature of the shield load and the resulting deformation, the strain gauge may detect a shortening or lengthening of the shield. Although the deformation patterns can be complex, the simple deformation patterns shown in Figure 3 can be useful in evaluating what is happening to the shield based on strain measurements.

Under a uniform stress field, or hydrostatic stress, the shield will experience a uniform compressive strain as shown in Figure 3a. External groundwater pressure is the most common example of uniform stress acting on a TBM shield. If the groundwater pressure increases, strain gauges on the shield detect a relatively consistent magnitude of compression and the circular shape of the shield is maintained.

Table 1. TBM shield dimensions for the Arrowhead Tunnels

Shield	Length	Diameter	Thickness
Front	3.665 m/12 ft-0 in	5.79 m/18 ft-11.5 in	70 mm/2.75 in
Middle	3.275 m/10 ft-9 in	5.77 m/18 ft-11 in	70 mm/2.75 in
Tail	3.875 m/12 ft-8 in	5.75 m/18 ft-10.5 in	60 mm/2.36 in

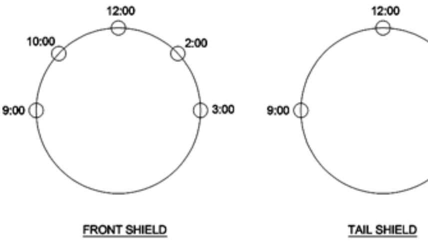


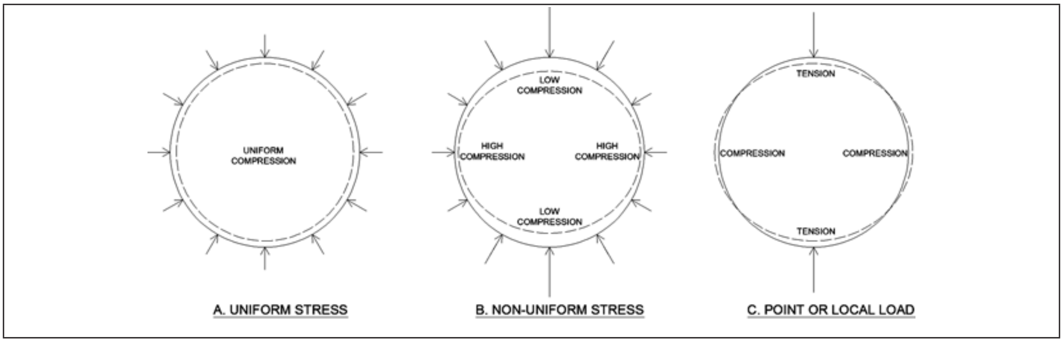
Figure 2. Location of strain gauges around TBM shields (looking toward the face)

Under a non-uniform compressive stress, different parts of the shield experience varying magnitudes of compression, causing ovaling of the shield. This phenomenon is, of course, not perceptible to the human eye, but can be easily detected with strain gauges. Figures 3b and 3c show non-uniform shield compression with greater shield deflection in the vertical direction (i.e., ovaling). In Figure 3b, a strain gauge mounted in the crown will tend to measure little or no compression, whereas strain gauges at the sides would measure greater compression. The opposite would be true if greater loading were applied at the sides of the shield.

Local or point loading can lead to greater ovaling of the shield, as shown in Figure 3c. This is more likely if the shield is not in complete contact with the ground, due to minimal ground convergence in stable conditions or to voids developing around the shield from overbreak or erosion. As the unsupported portion of the shield deforms into the void or annular space, a strain gauge on the inside of the shield detects compression. Some examples of localized shield loads include loosened ground loads and the asymmetric loads produced in steering a TBM through a curve.

The deformations shown in Figure 3 are idealized, and serve mainly as an introductory framework for interpreting the shield strain measurements. Actual shield deformations are more complex and may combine more than one deformation pattern. In many cases, strain measurements alone are insufficient to draw conclusions about the cause of a particular strain pattern. In such cases, strain measurements should be used in conjunction with information about construction activities, TBM performance parameters, knowledge of general geologic conditions at the face, and geologic site models. In attempting to interpret loading conditions based on strain measurements, the following factors must be considered:

- Different types of loads can occur at the same time (i.e., ground convergence and TBM steering loads).
- The shield is not always in complete contact with the surrounding ground.
- The gap between the shield and the ground is variable because the shield rests at the bottom of the excavation.
- Shear stresses between the shield and ground may affect the distribution of strain.
- Loads may be imposed by the injection of lubricating agents around the shield or by pre-excavation grouting.



A. UNIFORM STRESS

B. NON-UNIFORM STRESS

C. POINT OR LOCAL LOAD

Figure 3. Idealized TBM shield deformation patterns

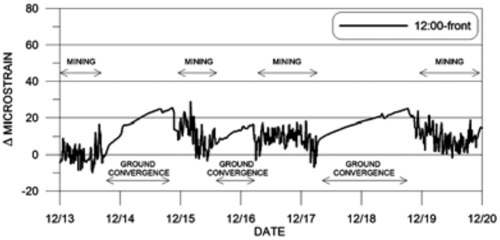


Figure 4. Strain-time history from the front shield while mining through stable ground conditions

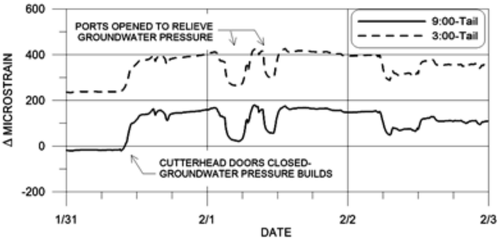


Figure 5. Strain-time history of hydrostatic load on the Arrowhead East Tunnel tail shield

FIELD-MEASURED STRAIN PATTERNS

Several examples of TBM shield strain patterns from the Arrowhead Tunnels are presented in Figures 4 through 9. These show a range of loading conditions. Not all strain gauges are shown for each scenario in the accompanying graphics. Only strain measurements from gauges that are representative of the scenario being illustrated are shown. A compressive change in strain is represented by an upward trend in the example strain-time history plots, while a downward trend represents a tensile or less compressive strain change.

Excavation Under Stable Ground Conditions and the Baseline Strain Concept

Ideally, strain gauges would be mounted to the shield prior to launching the TBM, and baseline (unloaded) measurements would be taken, so that all strain measurements obtained in the ground could be compared to a baseline. On the Arrowhead Tunnels Project, the idea of using strain gauges was developed after the TBMs were launched, so a truly unloaded reference or baseline strain could not be observed. Instead, the nearly unloaded state of the shield that exists immediately following the completion of a mining cycle in stable ground with low convergence was used as the baseline condition. The method used to determine this baseline strain is described in the following paragraph.

Figure 4 shows a strain-time history for one strain gauge from the front shield during several mining cycles under favorable ground conditions which could be used for developing a baseline or reference strain. The mine cycle is characterized by periods of mining separated by periods when the TBM stopped for probe drilling, pre-excavation grouting, and TBM maintenance. During mining, the strain signature is noisy due to the TBM vibrations and propulsion forces. At the end of a mining cycle, the shield is relatively unloaded but a small ground convergence load develops around the shield while the TBM has stopped. The magnitude of the strain increase from the ground load is commonly less than 50 microstrain on the front shield in good ground. The baseline strain is simply the lowest set of points on the strain history that correspond to the end of mining when there is no significant load acting on the shield. As shown in Figure 4, the stain history can be shifted so that the baseline strain is set to zero.

Groundwater Pressure

When high groundwater inflows occur at the face, doors in the cutterhead bulkhead can be closed to seal out water in order to maintain dry working conditions in the TBM. Figure 5 shows the build-up of hydrostatic groundwater pressure around the shield following a partial collapse of the tunnel face when the Arrowhead East TBM was advanced into a weak, highly altered rock mass. The TBM advance was halted in order to stabilize the ground with consolidation grouting, and the bulkhead doors were shut as water began filling the cutterhead plenum.

Because of the presence of weak ground in the face, there was concern that the ground might squeeze and trap the TBM. In reviewing the strain histories it was evident that the front and tail shields were being compressed more than normal, but it was determined that nearly all of the strain increase was coming from the build-up of groundwater pressure rather than ground load. The evidence for this conclusion was: (1) the time of the sudden increase in strain could be correlated to the time that the bulkhead doors were shut, and (2) the strain increase per strain gauge was uniform around the front and tail shields. Periodically the groundwater pressure was relieved through ports around the shield and a corresponding decrease in the shield compression was registered by the strain gauges. Following consolidation grouting, the TBM was able to advance ahead without much problem.

High Ground Convergence Load

It is generally understood that after excavation ground around a tunnel will displace inward, or converge, in response to stress redistribution. The

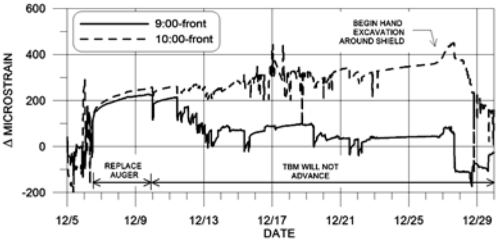


Figure 6. Strain-time history of a TBM stoppage due to muck packing and ground convergence

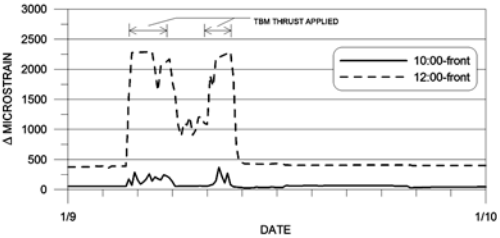


Figure 7. Sudden change in the strain level while thrusting due to a jammed TBM shield

amount of convergence depends on the in situ stress condition and the properties of the surrounding ground mass. Because the gap between the shield and the ground is often very narrow, the shielded TBM can be susceptible to high ground convergence loads even if the ground mass is not overstressed and squeezing. This tendency can be exacerbated by the packing of sandy muck around the shield (caused by advancing the TBM faster than the cutterhead chamber can be mucked out), which significantly reduces the annular gap between the shield and the ground and increases the skin friction between the shield and the ground.

Figure 6 shows the strain history for a TBM stoppage that was attributed to the excavation of a weaker rock mass and the severe packing of fine-grained muck around the shield. Hand excavation was eventually required around the shield to free the TBM. During the excavation, the screw auger used to remove excavated material from the cutterhead chamber was observed to be less efficient due to wear of the auger flights. The TBM began climbing in elevation due to increased packing of muck beneath the shield. At the completion of the mining cycle, poorer ground conditions had been encountered and the replacement of the worn auger commenced.

During the three-day maintenance period, a 200 to 250 microstrain compression loaded the front shield and an equivalent strain loaded the tail shield. Attempts to free the TBM were made by installing auxiliary jacks for additional thrust, flushing the annulus with high pressure water, and chipping away the rock mass from a limited number of circular ports in the shield. The strain gauge data allowed the effects of these remediation measures to be evaluated. Figure 6 shows that the remedial measures helped reduce the load at the 9 o'clock position, but not at the 10 o'clock position closer to the crown, where ground load continued to accumulate.

Inability to reduce the shield load led to the decision to hand mine around the TBM to free it. The excavation commenced at the front of the TBM and progressed to the back of the shield, creating a nearly 1 m (3 foot) opening over the top of the TBM from the springline to springline. As the excavation approached the location of the strain gauges, additional shield compression was detected as load was shed from the front of the shield to the back of the shield. This was observed on December 27 on the front shield (see Figure 6) and approximately a week and a half later on the tail shield. The strain decreased to the baseline strain once the excavation had passed the strain gauge location. At the end of the hand excavation over the shields, the TBM was free to advance.

Jammed TBM Shield

TBM stoppages at the Arrowhead Tunnels have sometimes been attributed to the shield of the TBM jamming into the tunnel sidewall. The occurrence is similar to a soft ground shield that might become "iron bound" if it is angled too severely in the tunnel, which can happen if the TBM gets out of alignment and the steering is overcorrected. When an attempt is made to thrust the TBM forward, a sudden increase or decrease in strain can be detected on one or more strain gauges. When the thrust is no longer applied, the elevated strain may return to prior levels or stay elevated. Figure 7 shows an example. It should be noted that the strain measurements over 2000 microstrain at the 12 o'clock front shield position are not considered correct because the deformation at this location exceeded the accurate range of the strain gauge. However, the pattern is consistent with the 10 o'clock strain gauge.

Localized Weak Ground

As a TBM passes through a weak geologic feature such as a fault or shear zone, the shield strain at any one location can change from tension to compression or vice versa. This is especially true if the feature crosses the alignment at a low angle rather than perpendicularly. Figure 8 depicts the strain-time history of the Arrowhead East tail shield as the TBM passed through a zone of sheared rock which was mapped in the face. During the first half of the day

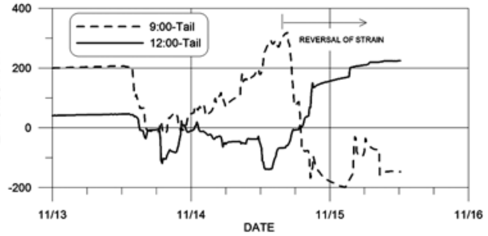


Figure 8. Strain development on the tail shield during the excavation through a local weak zone of ground

on November 14, the 12 o'clock tail shield strain gauge registered a relatively low tensile strain and the 9 o'clock tail shield registered an increasing compression strain. After mid-day, the trend reversed as the TBM advanced, with tension developing at the springline and compression developing on the crown. This pattern suggests that a localized load that was first acting on the crown was later shifted to the left springline. Perhaps coincidentally, this loading pattern occurred near a location where the tunnel was expected to encounter a fault striking subparallel to the tunnel alignment with a moderately steep dip. The fault was expected to be encountered at the top of the excavation, which would then move downward to the left as the TBM advanced; this pattern was consistent with the interpretation of the strain gauge measurements.

Hydrojacking Induced by Pre-excavation Grouting

On at least two occasions on the Arrowhead Tunnels Project, shield strains related to pre-excavation grouting ahead of the tunnel face have been observed. The strain-time history from the first of these incidents is shown in Figure 9. The source of the loads was not immediately recognized. The nature of the shield loading was unique in two respects: (1) the relatively large strain increase that developed occurred a few hours after the end of the mining cycle, suggesting that it was not a ground convergence load; and (2) the strain stopped increasing at the end of the graveyard shift before the weekend break. The strain on the shield held constant over the weekend until the following Monday afternoon on June 16 when the strain increased an additional 60 microstrain and again held constant until a TBM advance was attempted. The strain increase was observed on both the front and tail shields. In both cases, the initiation of the strain increases correlated to pre-excavation grout injections into specific grout holes ahead of the tunnel face. This was considered remarkable, considering the packers used for grouting were situated 30 feet ahead of the face.

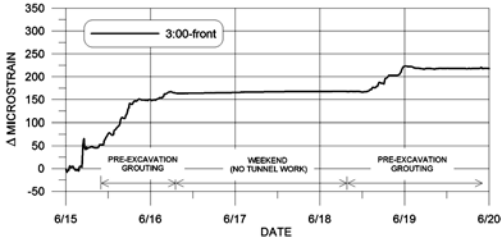


Figure 9. Strain-time history of pre-excavation grouting induced shield loading

A detailed analysis of the grouting records and incremental strain increases during the first grouting episode from Figure 9 is presented in Figure 10. This plot shows the incremental strain change between 10-minute strain measurements and the average cement injection rate calculated every 15 to 20 minutes. Although there is not exact synchronicity between the two sets of measurements, there are strong correlations between several large strain increases and the grout injection rates. The second grouting episode shown in Figure 9 showed a similar strong correlation.

Because the strain increase was cumulative and did not dissipate with time, it does not appear that loading on the shields was due to fluid grout pressure. Instead, it was hypothesized that the actual load on the shield was related to hydrojacking the ground into the annular space around the shield. This hypothesis is further supported by the strong correlation of strain increases with the volumetric grout injection rate.

IMPLEMENTING A STRAIN MONITORING PROGRAM

Components of a Strain Measuring System

A TBM strain monitoring system may be constructed in two ways: the easier way (during TBM fabrication), or the harder way (afterward). For the Arrowhead Tunnels Project, the decision to monitor strain levels on the shield was made after the TBM was on-site, so the task was a bit more difficult due to limitations on access for installation of sensors, cables, and the datalogger. In either method of construction, the components of the system are similar. They are:

- Strain sensors and cables
- Datalogger system
- Communication line to outside the tunnel

The strain sensors used on the Arrowhead Tunnels Project were Geokon model 4150 vibrating

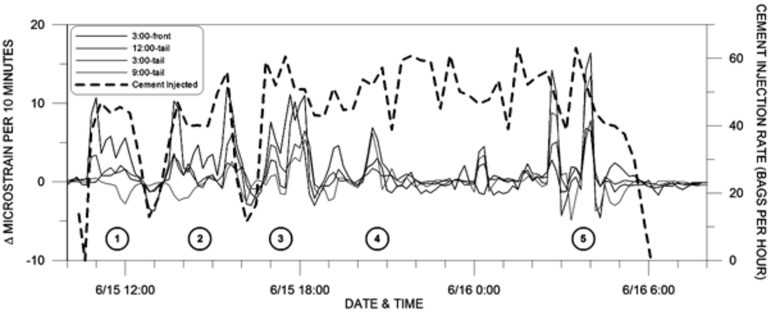


Figure 10. A comparison between strain changes and the rate of cement injection during pre-excavation grouting. Several prominent correlations between strain increases and cement injections are labeled.

Figure 11. Vibrating wire strain gauge

wire sensors. These sensors (depicted in Figure 11) can be attached using an adhesive, but it is preferable to attach them using a specialized spot welder, as was done for the Arrowhead project. Each sensor was ordered with about 10 meters (30 feet) of cable, which is enough to extend from the sensor location to the datalogger. The spot-weldable 4150 sensors were selected because their small size made them easy to install and protect, particularly on the tail shield, where clearances were tight due to space requirements for concrete segment erection.

The datalogger system shown in Figure 12 consisted of a watertight steel enclosure and the following internal components, which were obtained from Campbell Scientific, Inc.:

- Model CR10x datalogger (now superseded by model CR1000)
- PS100 power supply (12vdc rechargeable) and 110vac charger
- Vibrating wire interface (signal converter; milivolts to frequency signal)
- AM 16/32 multiplexer (provides the ability to read many sensors)

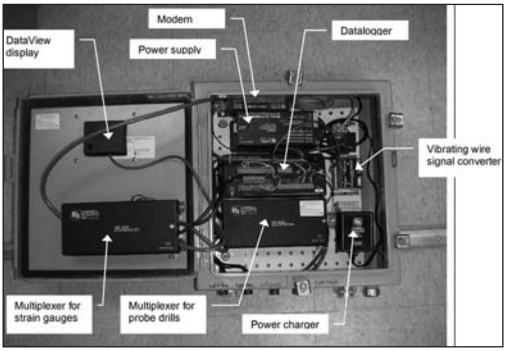


Figure 12. Datalogger enclosure, showing internal components

- Comm 210 modem (for data transmission)
- DataView (display panel; provides for viewing data in the tunnel)

It is noted that the datalogger system also included a second multiplexer to provide for simultaneous monitoring of the TBM probe drills, which is the subject of a different paper.

The datalogger components were installed in the enclosure, and wired to panel-mounted external plugs. These plugs allowed for easier installation and maintenance, and provided for quick connections to the cables for the sensors, power supply, and communication. The datalogger enclosure (before installation in the TBM) is shown in Figures 13 and 14.

The “DataView” display that was mounted on the face of the enclosure provided a means to check time and sensor readings in the tunnel heading. This was more important for tunnel inspectors who were observing the probe drilling, but was also useful for checking operation of the strain sensors.

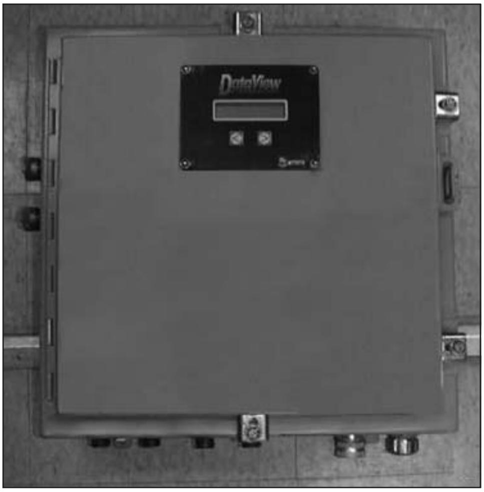


Figure 13. Datalogger enclosure before installation in the TBM

The telephone communication line was provided by the construction contractor, who had an existing fiber optic communication line extending from the job site office to the control cab in the TBM. As a result, the additional communication line for the datalogger only needed to extend from the TBM cab to the datalogger enclosure.

Hardware Installation and Maintenance

In principle, the components of the strain monitoring system, and its operation, are fairly simple. The more interesting challenges relate to its installation and maintenance in the confines of a TBM, and the difficulty of avoiding damage from the rough environment in a TBM. For example, the TBM commonly requires major maintenance, such as replacing the screw auger or working on large hydraulic jacks. These activities often result in sensor cables being cut. In addition, work related to probe drilling and changing cutters often causes cable damage.

The datalogger was installed near the instruments to be monitored (strain sensors and probe drills), where there was adequate space for the box, where it could be easily accessed for maintenance and checking the data display, and (most importantly) where there appeared to be less risk for damage. The final location (shown in Figure 14) was selected by both the owner and the contractor. Because the datalogger was located just below an expensive component of the laser guidance system, the potential for damage was lower.

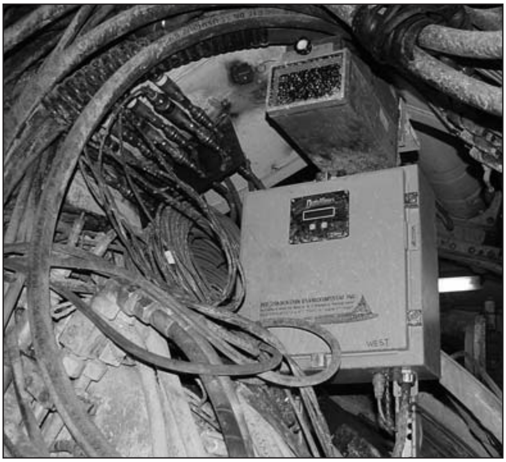


Figure 14. Datalogger enclosure after installation in the TBM

Initially, the strain gauges were installed on just the front shield: at springline on both sides, and in the crown. At all three locations, a pair of gauges was installed. One of each pair was oriented horizontally (parallel to the axis of the TBM), and the other was oriented along the circumference of the shield. The gauges were located about midway between major reinforcements within the shield (to avoid stress concentrations). After evaluating the data collected, it was concluded that the horizontal gauges were not as useful as the others for evaluation of ground loads, and so their use was discontinued. Because initial data appeared to be quite useful in evaluating loads on the shield, supplemental gauges were later installed at the quarter-arch points in the front shield. In addition, gauges were installed at both springlines and in the crown on the tail shield.

Steel covers were tack-welded over the sensors on the front shield to protect them from damage. Considering the thickness of the TBM shield (70 mm), the influence of these tack-welded covers on the gauge readings could be neglected. These covers worked well, and few sensors were damaged.

To avoid conflicts with segment erection, the sensors on the tail shield could not protrude into the shield more than about 6 to 12 mm (1⁄4 to 1⁄2 in). Thus, they had to be installed in “pockets” that were cut into the shield. These pockets were about 50 mm (2 in) wide, 75 mm (3 in) long, and 12 mm (1⁄2 in) deep. They were created by hand, using a grinder. This was difficult work, particularly in the crown and particularly because the bottom needed to be very flat so the sensors could be attached without binding. These installations would be much easier to accomplish if done during TBM fabrication.

Sensor cables were routed along paths that appeared least likely to be damaged. Even so, because they were exposed, the sensor cables were cut frequently, and repair of the cables was the most frequent maintenance issue. Sensor cables for the tail shield gauges were put in shallow channels that were cut into the shield using a hand grinder. The cables were covered with a strong, quick-drying adhesive to keep them in place and protect against damage.

Data Collection

The dataloggers could be programmed to record strain readings at whatever interval was desired, limited only by the time required to read all of the sensors (including both the strain gauges and probe drill sensors). In practice, the strain gauges were normally recorded at 10- or 15-minute intervals, whereas the probe drill sensors were monitored at 10-second intervals.

Data collection was done remotely, using telephone lines and specialized software developed by the instrumentation vendor (Campbell Scientific). The software provided options for scheduled data collection, as well as data collection at specific times that might be desired. Considering the amount of data being collected (6 to 11 strain gauges each 10 minutes, and 12 probe drill sensors every 10 seconds), and the amount of memory installed in the datalogger, it was decided to program scheduled data collection every two hours. Another factor considered in selecting the data collection interval was the fact that the data were being uploaded to a Web site for off-site evaluation. One computer in the field office was dedicated to programming, data collection, and Web site uploading; it ran continuously.

Analysis, Interpretation, and Reporting

The data collected from the dataloggers were formatted in comma-delimited ASCII format, so it was quite simple to create a spreadsheet to import the data, perform necessary calculations, and create charts of the results. The spreadsheet software was very useful for producing quick charts, but in some cases, more detailed charts were desired. Specialized X–Y plotting software was used for that purpose.

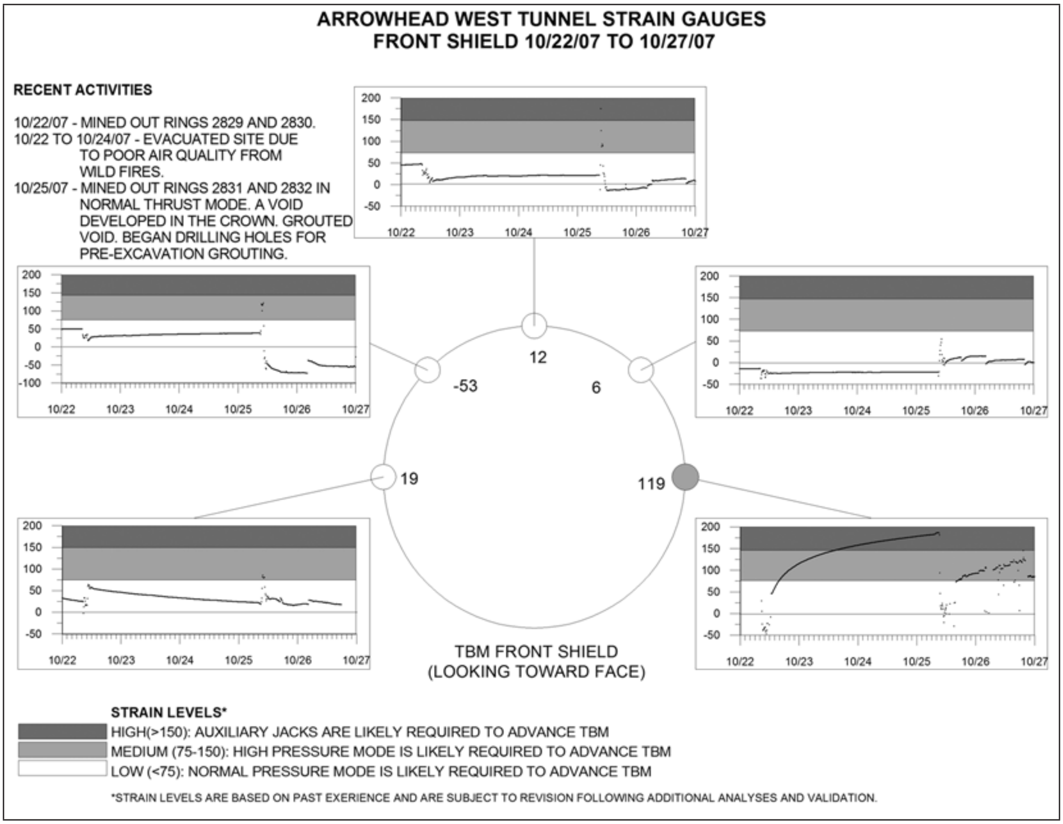
The evaluation of strain data can be completed in a few steps:

1. Import raw strain data into a spreadsheet. The raw strain data is stored in a data file which essentially consists of rows of dates and times with corresponding strain measurements from each of the strain gauges.
2. Arithmetically shift the data from each strain gauge so that the baseline strain is zero or nearly zero, as described above.
3. Make a strain-time history plot of the baselined strain data. Front shield strains are usually plotted separately from the tail shield strain because of the differing shield thicknesses.
4. From the strain-time history plots, note recent strain trends in terms of magnitude, direction (compression or tension), and rate of strain change.
5. Collect and evaluate information about what construction activities or geologic conditions were occurring at the time of strain pattern changes. Create a timeline of this information if needed.
6. Compare the timing of construction activities, TBM performance (TBM thrust, cutterhead force, etc.), and ground conditions to strain changes to identify factors that might be influencing changes in strain.
7. Annotate the strain-time history plots with the relevant additional information that helps explain recent trends.

A key issue with receiving and analyzing data is timeliness of reporting. The system for monitoring, analysis, interpretation, and reporting needs to provide quick feedback on data, from which decisions are made. Strains can develop on the TBM shield very quickly.

Attention to the reporting format is also important. Strain information will only be used if it is easy to understand and put into context. One way to put strain data into context is to define threshold strain levels between low and high shield loads that are likely to impair TBM advancement. For example, on the Arrowhead Tunnels Project, strain changes of less than 150 microstrain on the front shield usually do not cause significant delays in construction. However, changes of 150 to 200 microstrain or more often caused some form of delay in construction. Additional factors, such as the rate of change and the number of gauges showing similar effects also need to be considered in determining the severity of conditions. An example of a typical strain report provided to the owner's and contractor's personnel is shown in Figure 15.

The frequency of analysis and reporting depends on the needs of the project. As a general practice for the Arrowhead Tunnels Project, the trends and magnitudes of straining are checked at least daily, but formal reporting is much less frequent if the strains are low and mining progress is good. When the TBM is approaching poor ground, strains are checked several times during the day and reported on briefly or informally.



RECENT ACTIVITIES

10/22/07 - MINED OUT RINGS 2829 AND 2830.
10/22 TO 10/24/07 - EVACUATED SITE DUE TO POOR AIR QUALITY FROM WILD FIRES.
10/25/07 - MINED OUT RINGS 2831 AND 2832 IN NORMAL THRUST MODE. A VOID DEVELOPED IN THE CROWN. GROUTED VOID. BEGAN DRILLING HOLES FOR PRE-EXCAVATION GROUTING.

STRAIN LEVELS*

- ■ HIGH(>150): AUXILIARY JACKS ARE LIKELY REQUIRED TO ADVANCE TBM
- ▨ MEDIUM (75-150): HIGH PRESSURE MODE IS LIKELY REQUIRED TO ADVANCE TBM
- ☐ LOW (<75): NORMAL PRESSURE MODE IS LIKELY REQUIRED TO ADVANCE TBM

*STRAIN LEVELS ARE BASED ON PAST EXERIENCE AND ARE SUBJECT TO REVISION FOLLOWING ADDITIONAL ANALYSES AND VALIDATION.

Figure 15. Typical strain data report showing current strain levels and trends

CONCLUSION

Continuous monitoring of TBM shield deformation through strain measurements can offer beneficial information on the loading conditions on shielded TBMs. The data can be used to help substantiate conjectures about the causes of TBM delays or advancement problems due to shield binding or interaction with the ground, especially when such data are combined with information from geologic assessments, records of construction activities, and data about TBM performance. Analysis of the strain data should be performed regularly in order to detect increasing shield loads that may lead to a TBM stoppage. At the Arrowhead Tunnels, the main challenge in implementing a strain monitoring program was making room in the TBM for necessary hardware and keeping the system in working order in an active environment. The effort required to maintain the hardware components could be lessened if components were integrated into the TBM design and manufacturing such that the strain gauges and wiring were better protected.