Autonomous Condition Monitoring of an In-Service Historic Utility Tunnel

Submitted July 31, 2009
Word Count: 3990
Figure and Table Count: 11
Total Equivalent Word Count Including Figures: 6740

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ABSTRACT
Deep excavation for a new multi-use commercial building and subway station in the downtown Chicago “Loop” led to concern over possible disruptions of a century-old utility tunnel located only eight feet (2.4 m) from the edge of the site. The tunnel, which was dug by hand and lined with hand-poured unreinforced concrete, currently carries fiber-optic data connections for much of downtown Chicago. An autonomous Internet-enabled monitoring system consisting of displacement sensors, an embedded computer, communication hardware, and an automatically-updated, password-protected project Web site was installed in the tunnel to provide continuous performance data in a readily useful form for decision making. The system automatically recorded displacement measurements hourly for approximately two years, by which time the excavation was complete. City of Chicago personnel used the autonomously-generated reports from the Web site in daily construction meetings and had authority to halt construction in case of excessive displacement; ultimately, little movement was observed. This paper will discuss the instrumentation plan, robust communication from the instrumented section of tunnel to a telephone line several blocks away and on to the Web site, and strategies for reliable autonomous remote sensing in a challenging underground environment.
INTRODUCTION
Deep excavation for a new multi-use commercial building and subway station in the downtown Chicago “Loop” led to concern over possible disruptions of a century-old freight tunnel located only eight feet (2.4 m) from the edge of the site. The City of Chicago required careful monitoring of the tunnel during construction to prevent damage to the tunnel and the fiber-optic communication cables it contains. This paper will describe a part of that monitoring effort in which a network of displacement sensors was deployed in the tunnel to measure excavation-induced deformation. The system recorded displacement data hourly and automatically posted live data on a password-protected project Web site nightly for decision making by City of Chicago personnel.

This paper will discuss the motivation behind autonomous deformation monitoring, the instrumentation scheme, the often-trivialized issue of robust communication and reporting tools, the displacement results themselves, and issues of sensor and equipment survival. Strategies for instrumentation and communication in the freight tunnel, which presented many challenging conditions commonly found in geotechnical practice, will also be offered.

MOTIVATION
Deep excavation for redevelopment of the “Block 37” site along West Randolph Street between North Dearborn Street and North State Street required careful monitoring due to the presence of two century-old freight tunnels under Randolph Street. While one tunnel was abandoned, sealed, and grouted, the other — located a mere eight feet (2.4 m) from the excavation — contained communication infrastructure and remained in service during and after construction. The elevation view in Figure 1a shows the proximity of the active tunnel to the edge of the excavation, a reinforced concrete wall poured in a slurry-supported trench hereafter referred to as the slurry wall. Excavation-induced loss of lateral support behind the slurry wall might lead to deformation of the freight tunnel, as shown in Figure 2. Disturbance or failure of the tunnel would disrupt critical fiber-optic cables, shown in Figure 1b, which would easily result in millions of dollars of lost revenue for downtown businesses, including financial markets. Possible interaction between the freight tunnels and adjacent subway tubes was also of interest, particularly because the Block 37 redevelopment plan included a transfer station between the State Street and Dearborn Street subway lines.

The freight tunnels were dug by hand between 1901 and 1909 with little regulatory oversight — in fact, parts of the system were dug under the guise that they would be used only for telephone conduit, before the scheme to use them for freight and coal delivery was revealed (1). Crews used knives to gouge through the weak Chicago clay and poured the unreinforced concrete tunnel liner by hand (2). The irregular construction of the tunnel makes it especially difficult to predict its response to nearby construction.

FIGURE 1 (a) Elevation view of the Block 37 site looking west along Randolph Street, showing proximity of the in-service freight tunnel to the excavation — drawn after STS Consultants (unpublished data). (b) Photograph of tunnel interior showing communication cable conduit along the walls and standing water on the invert.
Monitoring Scheme

To ensure uninterrupted operation of communication and transit infrastructure in and near the Randolph Street tunnel, a scheme had to be developed to obtain meaningful measurements of the tunnel autonomously and continuously during the Block 37 excavation. Insofar as the freight tunnels resemble subway tubes, it should be noted that a variety of techniques developed for evaluating underground transit facilities are available. These include visual inspection, manual sounding with hammers or chain drags, impulse-response testing, ground-penetrating radar, thermography, laser surveys, and high-resolution photography to document defects (3). Of these, the most common is visual inspection (4). However, none of these are suited for autonomous operation — each requires visits by trained personnel and/or the permanent installation of equipment that would block passage through the tunnel.

To provide an autonomously-acquired, continuous record of deformation data, a monitoring scheme based on a network of sub-mil resolution (1 mil = 0.001 inch = 0.0254 mm) displacement sensors deployed on joints in the tunnel wall was selected to facilitate autonomous data collection and take advantage of a feature of the tunnels: because the concrete liner was poured by hand (2), there are distinct construction joints at irregular intervals along the tunnel. These joints form natural weak spots where deformation of the tunnel as a whole may be observed by measuring changes in the width of the construction joint. Fourteen construction joints were selected for displacement monitoring, and crack monitors (CMs) were installed across each. These joints were located in clusters near Dearborn and State Streets, where maximum deformation was expected (see Figure 2); a CM was installed near the midpoint of the block as well. A null transducer (i.e., a transducer not over a construction joint) was deployed in each of the three instrument cluster locations to measure any drift associated with electronics or deformation of the tunnel walls away from the construction joints. The utility of industrial displacement sensors in monitoring long-term crack displacement in structures is well established, and, in general, previous work has shown electronic drift to be negligible (5). The near-constant temperature in the tunnel also suggests that thermally-induced sensor drift would be minimal.

Displacement transducers were installed on the side of the tunnel most likely to be in tension according to the predicted deformation pattern (Figure 2), though the exact location of the inflection point was unclear. Crack monitors 1–3 and 12–14 were installed on the north side of the tunnel, and all others (including the three null transducers) were installed on the south side.

TRANSDUCER SELECTION AND INSTALLATION

Hermetically sealed LVDT-type displacement sensors — Macro Sensors model GHSD-750-250, with a range of ±250 mils (±6.3 mm) and, with support electronics described below, theoretical system resolution of 25 µin (635 nm) — were selected to measure the small expected displacements. The LVDT core is connected to a sealed spring-loaded shaft. The sealed sensor body was necessary to prevent deterioration in the high humidity, condensing tunnel atmosphere. The spring-loaded plunger-type shaft was chosen over the more common free-core LVDT to prevent binding in the event of out-of-plane movement: the sensor body was anchored such that the spring-loaded plunger bore upon a glass block anchored to the wall on the opposite side of the construction joint. A rounded stainless steel tip on the plunger allowed the tip to travel smoothly across a glass block in case of out-of-plane movement. The utility of glass blocks as dimensionally-stable target shims for crack displacement measurement was established by Waldron (6).

Special steps were taken to anchor the LVDT and target to the tunnel wall due to asperities in the concrete surface and dripping or even flowing water in some places. The LVDT was secured with jam nuts into the bracket...
shown in Figure 3a, and the bracket was affixed to the tunnel wall with a combination of 90-second fast cure epoxy for early strength and slow-cure marine epoxy putty for long-term strength. The stud welded on the back of the bracket was coated in epoxy and inserted into a hole drilled in the tunnel wall for extra strength. The plungers on all sensors were coated with silicone grease to prevent corrosion in the 100% humidity condensing environment, as volumetric expansion due to formation of rust would result in spurious displacement changes. Figure 3b is a photograph of a typical LVDT installation on the tunnel wall.

FIGURE 3 (a) Section view of LVDT and glass block target with brackets installed in tunnel wall, showing studs inserted into wall and use of epoxy putty to smooth over asperities while providing good bond. (b) Photograph of typical LVDT installation on tunnel wall.

DATA ACQUISITION AND COMMUNICATION

Data acquisition and robust communication are as important to remote monitoring as selection and placement of the sensors. Design of geotechnical remote sensing systems must consider the long distances involved in monitoring a large facility, harsh environmental factors, and the often-trivialized need to reliably transmit data off-site for analysis. The freight tunnel exemplifies these challenges: the instrumented section of the tunnel is approximately 350 feet long, and is over 700 feet from the nearest communication lines to the outside world, a telephone line in the sub-basement of City Hall. Communication and control electronics were installed in an enclosure near the telephone line. Industrially-rated components were used to resist the hot, humid, and dusty conditions in the sub-basement utility area. The most vexing environmental problem in the freight tunnels, as in many geotechnical facilities, was moisture, including water dripping from the walls and ceiling, standing water on the invert, and a 100% humidity, condensing atmosphere. These conditions required the specification of stainless steel LVDTs, watertight electrical connectors, and NEMA-4 watertight enclosures for support electronics.

In-Tunnel Electronics

The vulnerability to electronic interference of the extremely long cable run between the sub-basement location and the location of sensors within the tunnel necessitated the transmission of digital data rather than analog readings over that distance. The RS-485 protocol was chosen for this digital bus due to its high noise resistance and the multi-drop topology — that is, many analog-to-digital converters could use the same physical bus, eliminating the extra cable runs that would be needed if each required a dedicated cable. A single junction box was capable of reading up to eight individual displacement sensors. Each displacement sensor was made digitally accessible over the RS-485 bus through a CyberResearch CyMOD 4017 remote analog input module inside each junction box. Figure 4 shows the relative location of the junction boxes to the sensors which fed into each of them.

Power for the in-tunnel sensors and junction boxes was tapped from a dewatering pump located at the western end of the instrumented tunnel segment. Into this junction box, came the 110 VAC power from the dewatering pump as well as the long Category-5e communication cable from the control electronics in the sub-basement of City Hall. The electronics inside this junction box converted the 110 VAC power from the dewatering pump to 48 VDC, combined it with the communication lines, and fed it over one cable down the tunnel to the three junction boxes.

Attenuation due to soil and concrete walls made radio communication between the sub-basement tunnel entrance and the instrument locations impossible. To overcome this challenge, a two-endpoint telephone network was installed alongside the digital communication bus that ran down the length of the project. At each junction box, engineers were able to plug in a waterproof portable telephone base unit and communicate by voice with another engineer stationed at the tunnel entrance. This was crucial not only for the safety of the installation team but for the calibration of the individual gauges. During installation, an engineer with a laptop in the sub-basement gave voice commands to an engineer in the tunnel to position each gauge precisely in the middle of its operating range. This method was
FIGURE 4 Elevation view sketch of freight tunnel instrumentation scheme showing distribution of displacement transducers (blue squares) and junction boxes containing data acquisition electronics (red diamonds) along the Randolph Street tunnel.

convenient because it facilitated thorough test of the complete data acquisition and communication systems early in the installation process; also, any laptops brought into the tunnel itself would likely have been damaged by condensation from the atmosphere.

Basement Electronics
Control of and communication with the sensor network inside the freight tunnel was performed by a custom-built control system that resided in the sub-basement of Chicago’s City Hall just outside the entrance to the tunnel. Figure 5 shows the control system which featured a Moxa UC-7408-LX embedded GNU/Linux field computer with custom software, a Micro Seven LS15 telephone network emulator and telephone handset for communicating with engineers inside the tunnel, a Sixnet VT-MODEM-1 industrial telephone modem to communicate the data back to the lab, and CyberResearch CyMOD 4520 RS-485 communication hardware to query each sensor in the tunnel.

Robust Autonomous Data Acquisition
Once per hour, the control system would execute custom-built control software (C programs and shell scripts written in-house) that took one thousand readings over a period of several seconds from each sensor and averaged them to eliminate any electronic interference. These data were stored on a CompactFlash memory card in the embedded computer where they could be retrieved via telephone modem. Each night, an autonomous polling server in the lab connected via telephone modem to the computer in the sub-basement of City Hall. It downloaded the latest data and immediately posted them to the project’s secure Web site. In the event that the telephone modem was unplugged or the telephone line failed in any way, the system would simply store the data until communications were restored. This behavior allowed data collection to continue even when the telephone line was accidentally cut during the course of the various construction activities in the sub-basement. The system was capable of more frequent (e.g., hourly) reporting, but city officials deemed nightly updates sufficient.

Project Web Site
Autonomous data collection requires autonomous reporting for maximum utility. The project Web site was automatically updated each night with the latest displacement data. The site was password-protected to prevent unauthorized access to the data. Built-in reporting capability facilitated easy analysis of trends and comparison to historical performance. That is, the Web site presented current and historical time history graphs from each displacement sensor in both screen- and print-friendly formats for quick evaluation at the computer screen and easy inclusion in written reports. A screen capture of the Web site is shown in Figure 6. The flow of data from tunnel sensors to Web site occurred nightly without human intervention.

RESULTS
In general, very little displacement was observed along the construction joints. The minimum and maximum values for each measurement point are shown in Table 1; the deformation time histories are plotted in Figures 7 and 8. Each sensor was centered at displacement = 0 at the beginning of the project; positive displacement indicates crack opening. CM-1, CM-7, CM-12, CM-13, and CM-14 steadily opened throughout the project, and CM-10 steadily closed. The
FIGURE 5 Communication box in the sub-basement of City Hall, showing embedded field computer with RS-485 support, telephone modem, power supplies, and telephone network emulator for in-tunnel voice communication.

FIGURE 6 Screen capture of Block 37 web site showing customizable plots of freight tunnel joint displacement data.
other CMs did not exhibit any overall trend. Figure 9 shows the relative magnitude of construction joint displacement at each instrumented location. The greatest deformations — though they were small — occurred at the east and west edges of the instrumented section, near the corners of the Block 37 excavation.

**TABLE 1** Maximum and minimum recorded displacements, total range of movement (i.e., maximum – minimum), and approximate survival time of each transducer during the project. + indicates transducer survived entire 25 month duration of project. Positive displacement indicates crack opening.

<table>
<thead>
<tr>
<th>CM</th>
<th>Minimum Displacement (mils/mm)</th>
<th>Maximum Displacement (mils/mm)</th>
<th>Range ((\delta)) (mils/mm)</th>
<th>Survival Time (months)</th>
<th>Notes from Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-2 -0.05</td>
<td>47.1 1.20</td>
<td>49.1 1.25</td>
<td>+</td>
<td>Target slightly loose</td>
</tr>
<tr>
<td>2</td>
<td>-37 -0.94</td>
<td>8.4 0.21</td>
<td>45.4 1.15</td>
<td>20</td>
<td>Target tightly loose, much water</td>
</tr>
<tr>
<td>3</td>
<td>-1.2 -0.03</td>
<td>7.5 0.19</td>
<td>8.6 0.22</td>
<td>+</td>
<td>Some water</td>
</tr>
<tr>
<td>4</td>
<td>-8.5 -0.22</td>
<td>0 0</td>
<td>8.5 0.22</td>
<td>+</td>
<td>Some water</td>
</tr>
<tr>
<td>5</td>
<td>0 0</td>
<td>17.4 0.44</td>
<td>17.4 0.44</td>
<td>+</td>
<td>Some water</td>
</tr>
<tr>
<td>Dearborn Null</td>
<td>-5.1 -0.13</td>
<td>0 0</td>
<td>5.1 0.13</td>
<td>+</td>
<td>Some water</td>
</tr>
<tr>
<td>6</td>
<td>-1.4 -0.03</td>
<td>1.7 0.04</td>
<td>3.1 0.08</td>
<td>13</td>
<td>Considerable mineral deposits</td>
</tr>
<tr>
<td>7</td>
<td>-0.1 0</td>
<td>6.5 0.16</td>
<td>6.6 0.17</td>
<td>+</td>
<td>Dripping water</td>
</tr>
<tr>
<td>8</td>
<td>-1.7 -0.04</td>
<td>0.9 0.02</td>
<td>2.6 0.07</td>
<td>14</td>
<td>Dripping water mineral deposits</td>
</tr>
<tr>
<td>Midpoint Null</td>
<td>-4.5 -0.11</td>
<td>0.3 0.01</td>
<td>4.8 0.12</td>
<td>20</td>
<td>Some water</td>
</tr>
<tr>
<td>9</td>
<td>0 0</td>
<td>10.2 0.26</td>
<td>10.2 0.26</td>
<td>+</td>
<td>Dripping water, mineral deposits</td>
</tr>
<tr>
<td>10</td>
<td>-8.9 -0.22</td>
<td>0.4 0.01</td>
<td>9.3 0.24</td>
<td>23</td>
<td>Running water after removal</td>
</tr>
<tr>
<td>11</td>
<td>-4.3 -0.11</td>
<td>2.0 0.05</td>
<td>6.3 0.16</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>State Null</td>
<td>-3.4 -0.09</td>
<td>4.5 0.11</td>
<td>7.9 0.20</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0 0</td>
<td>9.4 0.24</td>
<td>9.4 0.24</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>-0.1 0</td>
<td>3.1 0.08</td>
<td>3.3 0.08</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>-0.2 0</td>
<td>25.5 0.65</td>
<td>25.6 0.65</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

**Response to Non-Deformation Events**

In a few instances, events unrelated to tunnel deformation caused spurious readings. In particular, a few problems with the bond between the glass target block and its mounting stud arose. The target glue lines at CM-5, CM-7, and CM-9 failed early in the project and were replaced. The spurious data were ignored and the replacement targets showed no further problems. The glue line connecting the glass target block to its mounting stud became loose on CM-1 and CM-2 sometime during the second year of monitoring when access to the tunnel was not available and were not replaced.

**DISCUSSION**

Ralph B. Peck famously noted, “Every instrument installed on a project should be selected and placed to assist in answering a specific question (7).” Overall, the results from the CM gauges answered the question of did the freight tunnels deform significantly in the negative: most of the crack monitors indicated less than ten mils of movement.

The relationship between construction progress and the small CM responses is unclear. In the overall absence of large displacements at the crack monitors, it is particularly difficult to establish any sense of causality. A detailed study of construction records and surveys might yield a conclusion, but is beyond the scope of this paper.

**Long-Term Serviceability**

Geotechnical instrumentation must remain operable for the duration of a project to provide meaningful data for continuous monitoring, as in the two years of operation in the freight tunnel described here. The 100% humidity, condensing atmosphere and presence of dripping or running mineral-laden water in the tunnel — typical of subsurface environments — is very hostile to electronics. The steps taken to protect the instruments and support electronics from the environment were largely successful with a few notable exceptions. All the NEMA-4 electronics boxes remained perfectly dry, and the power supplies, analog-digital converters, and communication hardware inside functioned without disruption through the end of the project. Likewise, all communication cables (and associated connectors) remained...
FIGURE 7 Displacement time history on all Dearborn Street crack monitors during the course of the project.
FIGURE 8 Displacement time history on midpoint and State Street crack monitors during the course of the project.
All transducers remained operable from an electronic standpoint throughout the project. Six of the seventeen instruments were observed to have mechanically “frozen” plungers upon removal. The survival time of each sensor is indicated in Table 1. The fact that approximately one-third of displacement transducers mechanically froze during the course of the project warrants discussion. First, it is important to note that the failure was mechanical freezing or binding of the sensor plunger — almost certainly due to harsh environmental conditions, including mineral deposition on the plunger — and not a failure of the internal LVDT core or any kind of electronic failure. Second, the top-down construction of the Block 37 skyscraper lengthened the time required for excavation by a factor of four or five, so the amount of time the instruments were in the tunnel was much longer than may be typical of most excavation monitoring projects. Third, the excavation was complete approximately six months before the displacement transducers were removed; therefore, sensor failures that occurred more than 18 months into the project do not affect excavation-induced measurements. Furthermore, the removal of lateral tunnel support by the excavation occurred considerably before the excavation bottomed out, as illustrated by Figure 1a. Conservatively, no more than two sensors froze before lateral support was removed; 88% of sensors were operable at least until tunnel lateral support was removed, and 82% of sensors were operable at least until the excavation bottomed out. Because access to the tunnel was restricted, no attempts were made to replace sensors that had frozen. In retrospect, the instrumentation scheme could have been made more robust by use of redundant sensors (though this would have increased the sensor and wiring costs considerably), or perhaps something as simple as a sheet metal cover over each LVDT to deflect dripping mineral-laden water.

Several sites (noted in Table 1) showed accumulation of mineral deposits on or near the sensors. One such location is shown in Figure 10. Curiously, there does not seem to be a strong correlation between the immediate presence of dripping or running water and freezing failure: of the seven crack monitor locations where water was noted, only two froze. The presence of mineral deposits on or near the transducer was only a slightly better indicator, as two of the four sensors where mineral deposits were observed on removal had frozen. Two sensors found to be frozen upon removal, CM-14 and the midpoint null, showed no signs of dripping water or mineral deposits. It is hypothesized that condensation may have led to those failures. Significantly, none of the LVDTs or target blocks showed any sign of rust which, if present, would cause spurious displacement readings.

Limitation of This Instrumentation Scheme

Instruments such as displacement transducers will, of course, measure deformation or damage if it occurs at the location of the instrument. These point measurements may not accurately represent the overall response of the facility. In this case, a number of point measurements may improve the utility of — and the engineer’s confidence in — the data (7). In this installation, a reasonable approximation of the tunnel response was obtained by displacement measurements at fourteen points, concentrated in two clusters 76 and 113 feet long, respectively.
FIGURE 10 LVDT showing accumulation of mineral deposits after two years in the tunnel.

Data-Driven Decision Making
Autonomous monitoring carries the distinct advantage of facilitating data-driven decision making. In spite of the limitations of the instrumentation scheme noted above, the continuous, autonomous collection of measurements from a number of instruments provides useful performance indicators that can be used in near-real time. The project Web site was updated autonomously nightly, and every morning, Chicago Department of Transportation personnel checked the Web site and brought the latest autonomously-generated report to construction meetings. These personnel had authority to halt construction in the event of unacceptable movements. The Web site also facilitated sharing of near real-time data among many individuals from a variety of agencies.

CONCLUSIONS
Based on the experience of this work, the following conclusions are drawn:

1. The instrumentation and continuous remote monitoring described herein proved both practical and useful over the two year life of the project.

2. When appropriately designed, off-the-shelf industrial displacement sensors and data acquisition electronics are reasonably well suited to conditions encountered in the freight tunnels and similar projects.

3. Robust communication is a critical aspect of autonomous reporting and must not be trivialized. That said, integration of industrial communication hardware — particularly with on-site intelligence such as an embedded computer — can create a useful system that is resistant to disruption and data loss.

4. A project Web site with live data facilitates data distribution among varied parties while keeping data secure from unauthorized access.

ACKNOWLEDGMENTS
This work was funded by the Northwestern University Infrastructure Technology Institute, a National University Transportation Center supported by the US Department of Transportation Research and Innovative Technology Administration. The authors wish to acknowledge the kind assistance of the Chicago Department of Transportation and STS Consultants in providing access to the tunnels and otherwise facilitating Northwestern’s involvement in the project.
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