KEEPING TABS ON TWO TUNNELS

How do you keep commuter trains running safely while a new tunnel is built less than 2 m above an existing subway tunnel? Engineers devised a unique system to monitor vertical movements of the older tunnel during construction of the new one.

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Maintaining safe tunnel conditions for subway commuters is essential to the Fort Point Channel Crossing project, part of Boston's massive Central Artery Tunnel (CA/T). As part of the $10.5 billion Massachusetts Highway Department project, new immersed tube tunnels are being constructed about 1.5 m above existing twin subway tunnels. More than 10,000 commuters per hour pass through these Massachusetts Bay Transportation Authority (MBTA) Red Line tunnels during peak travel times. The MBTA required continuous, uninterrupted subway service during CA/T construction.

Our firm, Shannon & Wilson, was part of the design team that included Bechtel/Parsons Brinckerhoff, Boston, management consultant for the CA/T, and Gannett Fleming Inc., Braintree, Mass., section design consultant. With GeoKon, Lebanon, N.H., we designed and installed a unique instrumentation program to monitor the structural integrity of the concrete subway tunnel liners throughout construction.

The system is based on comprehensive numerical soil/structure interaction analyses, detailed geotechnical subsurface explorations, laboratory analyses of concrete liner cores and structural condition surveys of the concrete liners. We used nondestructive geophysical methods, including ultrasonic and ground-penetrating radar testing. We installed more than 1,000 gauges in the tunnels to monitor differential vertical movements, concrete joint and crack openings, concrete surface strain change, vibrations and water flow.

We can monitor all the instruments remotely through an automated data acquisition system. Data can be processed and results plotted with a database program in about two and a half hours during the most critical construction periods.

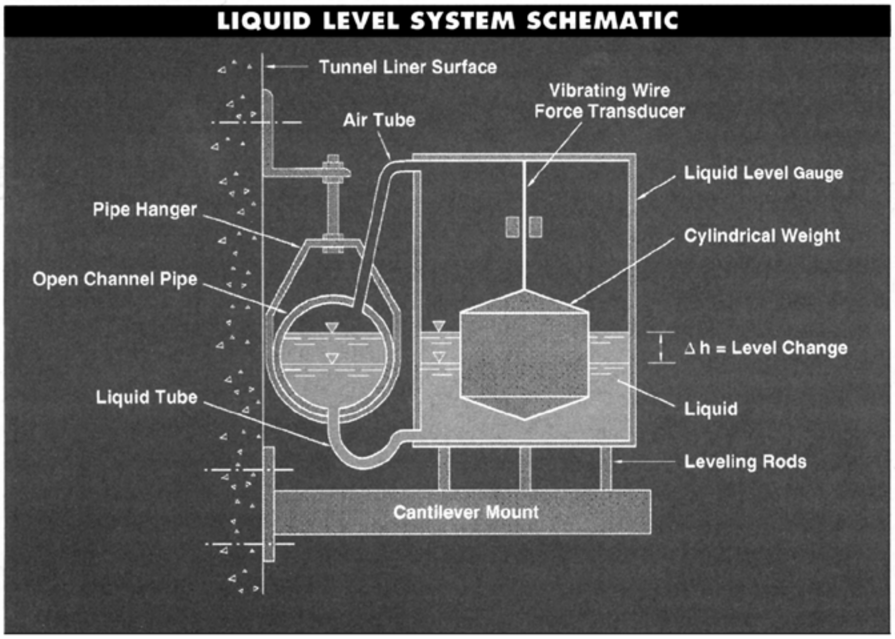
RED LINE TUNNELS

The Red Line, built in 1916, consists of twin tunnels beneath the Fort Point Channel waterway, with an overburden of approximately 2.4 m of soft organic deposits underlain by about 6 m of soft to stiff Boston blue clay. The tunnel liner system comprises 23 cm of wood covered by a 60 cm of concrete, generally unreinforced.

The tunnels could undergo a maximum of about 13 mm of differential movement as a result of adjacent CA/T dewatering and dredging. Vertical differential movements, either settlement or heave, would have a significant impact on the structural integrity of the tunnels. Movement can cause construction joints to open, which could damage the waterproofing membrane and result in leaks.

We considered several alternative instrumentation systems to monitor tunnel movement, including optical level surveys, bore hole extensometers, tiltmeter strings, optical lasers and a liquid level system. Each was

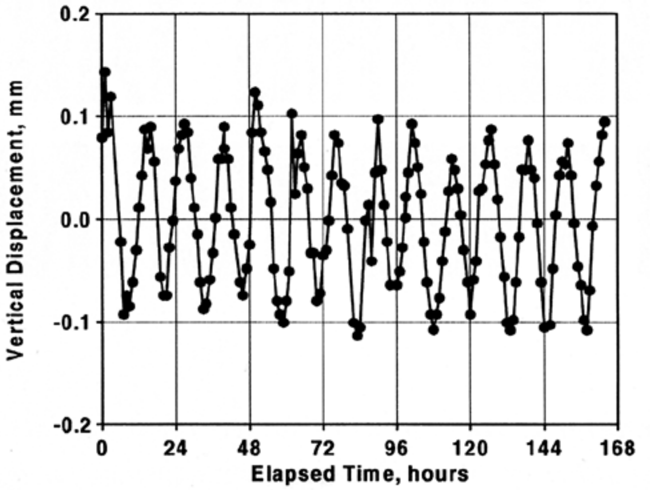
LIQUID LEVEL SYSTEM SCHEMATIC



evaluated according to the results of numerical analyses, tunnel access restraints, and ease of collecting and processing the data.

We set performance requirements, based on our data, for monitoring vertical movement. These included a sensitivity of 0.05 mm, repeatability of 0.1 mm and accuracy of 0.20 mm. Considering these requirements and the need to monitor the tunnels rapidly during MBTA revenue and nonrevenue periods, we selected the liquid level system.

VERTICAL DISPLACEMENT AT A TYPICAL LIQUID LEVEL GAUGE SHOWING DISPLACEMENTS CAUSED BY TIDES

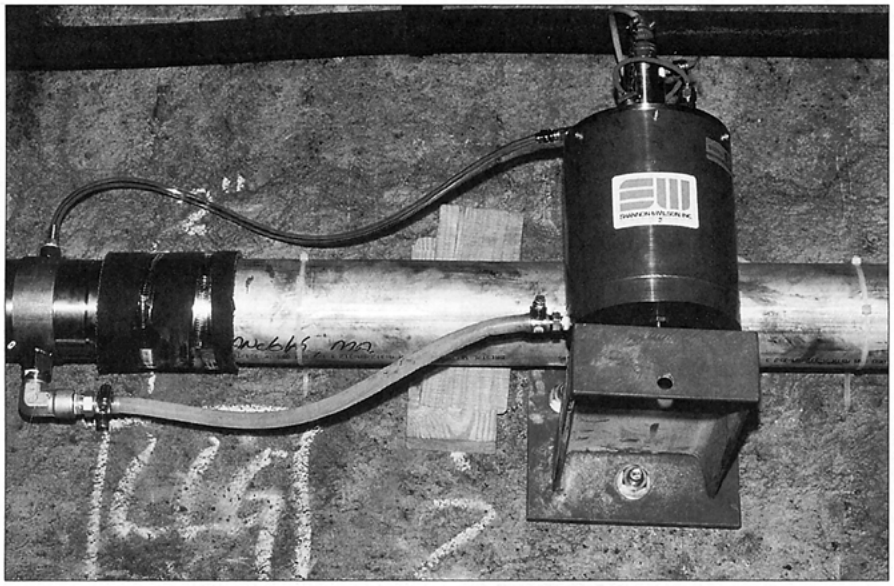


LIQUID LEVEL SYSTEM

All liquid level system components, including gauges and carrier pipes, are fireproof and are made of noncorrosive materials. To maintain adequate tunnel clearance, no part of the system projects more than 30 cm from the tunnel wall.

The liquid level system is based on hydraulic communication between chambers connected in sequence by a fluid-filled tube. Differential vertical movement of any pair of chambers generates a rise or fall of fluid level. There are many ways to measure the liquid level change: magnetic induction sensors or capacity sensors in combination with floats on the liquid surface; ultrasonic transducers that measure sonic pulses reflected from the liquid surface; and pressure transducers that directly measure the change in the liquid level. None of these offer cost-effective high accuracy. However, using force transducers to measure the weight of liquid in a chamber or the buoyant force of a partially submerged mass is cost effective and highly accurate.

With GeoKon's John McRae, we developed a liquid level gauge that uses force transducers. We also developed a liquid density gauge to measure changes brought about by temperature or long-term chemical changes in the fluid. Unlike the liquid level gauge, which includes a partially submerged cylindrical weight, the liquid density gauge includes a weight totally submerged in the fluid. A vibrating wire force transducer suspends the weight. We chose the transducer because of its exceptional zero stability and sensitivity, its ability to transmit a stable signal over long distances, its relatively simple mechanical design and its negligible temperature sensitivity.



THE LIQUID LEVEL SYSTEM, MOUNTED ON THE WALL OF BOSTON'S RED LINE SUBWAY TUNNELS, MONITORS STRUCTURAL INTEGRITY WHILE A NEW TUNNEL IS BEING BUILT 1.5 M ABOVE.

LIQUID LEVEL AND DENSITY GAUGES

Our firm, in conjunction with GeoKon, completed the final design of the gauges. Each consists of a vibrating wire force transducer, a chamber, a cylindrical weight, a lead cable, and liquid and air tubes for connection to the carrier pipe. The gauges have a locking mechanism to prevent movement of the internal weight during transport. The mechanism applies constant tension to the vibrating wire sensor when the gauge is locked. This prevents any mechanical, irreversible deformations of the vibrating wire and ensures repeatable performance of the gauge when it is in the unlocked position. Each gauge also contains a thermistor to measure the temperature of the liquid.

The force transducer assembly is mounted on top of a 15-cm-diameter by 20-cm-high chamber. A 10-cm-diameter by 9.5 cm high cylindrical weight is suspended from the transducer. The weight has a conical configuration to prevent air bubble accumulation at the bottom and condensation at the top. The transducer housing, chamber and weight are made of stainless steel, and the chamber and weight have a Teflon-like coating to reduce liquid adhesion. The liquid level gauge has a range of 38 mm, an accuracy of 0.20 mm, a repeatability of 0.10 mm and a sensitivity of 0.05 mm. The liquid density gauge has an accuracy of 0.5% of the fluid density.

LIQUID CARRIER PIPE

To maintain the long-term accuracy of the liquid level system, the design minimizes the following potential sources of large systematic errors normally inherent in liquid level systems: air bubbles, air pressure differences, the inability of the system to quickly return to equilibrium after a dynamic disturbance, and liquid density variations due to temperature differences.

A typical liquid level system consists of tubes 6 to 19 mm in diameter. The cross section of the tubes is entirely filled with liquid. The system tends to develop air bubbles that plug the hydraulic communication from one gauge to the next. To avoid this, we used an open channel for most of the Red Line tunnel liquid carrier system. The carrier pipe is a 75 mm ID stainless steel pipe half filled with liquid. Liquid level gauges and liquid density gauges are connected to the carrier pipe by gauge couplings that consist of a 200-mm-long piece of 75 mm ID stainless steel pipe equipped with baffles and welded fittings. A closed system of this type prevents liquid evaporation and air flow into the system. It also equalizes air pressure throughout the system and isolates the liquid level system from pressure changes in the tunnel caused by passing trains and ventilation fans. Baffles in the gauge couplings damp any disturbance of the liquid surface that may occur in response to vibrations from passing trains.

The liquid level system is based on hydraulic communication between chambers connected in series by a fluid-filled tube. Differential vertical movement of any pair of chambers generates a rise or fall of fluid level.

Because the liquid density variations related to temperature differences are minimal for a maximum liquid height of 7.5 cm, only one liquid density gauge was installed in each carrier pipe system. Direct liquid density measurements allow corrections for liquid density changes brought about by long-term chemical reactions between the stainless steel and liquid in the system.

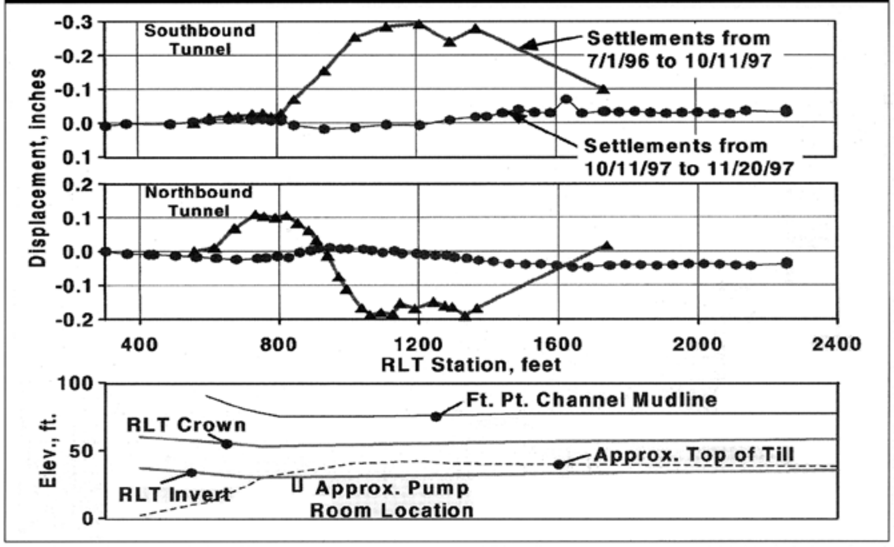
The liquid is steam-distilled water with a small concentration of chlorine to inhibit organic growth, chosen for its low coefficient of thermal expansion and low viscosity and because the fluid is not subject to freezing.

SYSTEM IMPLEMENTATION

We conducted a pilot program to evaluate the proposed final design configuration, installation procedures, and the sensitivity and repeatability of the liquid level gauges and liquid density gauges. The performance of all system components and of the proposed automated data acquisition (ADA) systems was monitored over a period of several weeks. Testing included a complete evaluation of system performance during MBTA operating and shutdown periods. During the tests, we evaluated the repeatability, sensitivity and accuracy of the liquid level gauges. We also examined reading stability under various influences such as the influence of temperature variations, dynamic disturbances during train traffic, and the presence of the third rail and high-voltage lines.

In the first test, we periodically added 500 mL of water to the system and then removed it. This liquid volume change corresponded to simultaneous changes of the water level in all three liquid level gauges equal to 0.14 mm. Subsequent tests consisted of several cycles of precisely raising and lowering one of the gauges by an average of 11 mm. The change in gauge height was measured with dial gauges. During all the movement cycles, the liquid level gauges were monitored every 30 seconds.

TYPICAL VERTICAL DISPLACEMENT MEASUREMENTS FROM LIQUID LEVEL SYSTEM



The pilot test indicated that all three liquid level gauges exhibited a short-term accuracy of 0.03 mm, a repeatability of 0.02 mm and a sensitivity of at least 0.001 mm, all well within the specified requirements.

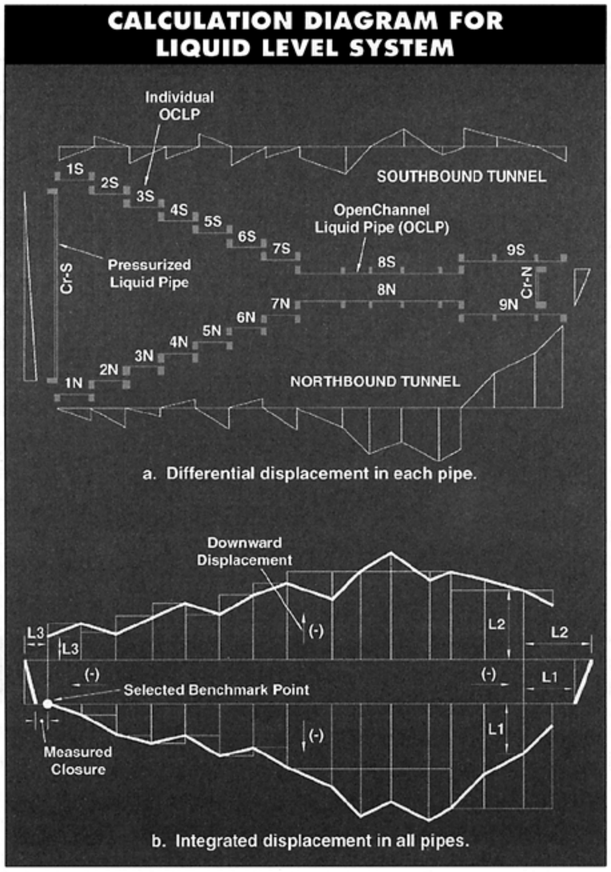
Additional long-term tests consisted of monitoring the liquid level gauges and the liquid density gauge for variable periods (from 30 seconds to an hour) for approximately three weeks to evaluate the stability of the readings during normal working conditions in the tunnel. The tests indicated that the readings for all gauges were stable and varied by no more than 0.05 mm daily and 0.10 mm during the three-week monitoring period. The daily variations were distinctly cyclic, with two full cycles per day, reflecting the daily lunar tide cycle. The variations over the three-week period followed a cycle that may have corresponded to the 28-day lunar cycle. The long-term readings do not appear to have been affected by the high-voltage lines, the third rail or train passage. The long-term tests showed the same repeatability and sensitivity of the gauges as had been established in the short-term tests.

Monitoring the gauges every 30 seconds during normal daytime train traffic indicated large disturbances. These disturbances, however, typically lasted less than 30 seconds, which indicated that the baffles, located within the couplings, were functioning properly.

The pilot program was extended throughout the Red Line tunnels to measure relative vertical displacements of the structure during the five-year CA/T construction period.

FULL-SCALE PROGRAM

We installed the final liquid level system in stages. During the first stage, a 365-m-long liquid level system was installed in each tunnel. In 1996, we placed carrier pipe along the length of the dredging corridor above the subway tunnels, along with a total of 48 liquid level gauges and nine liquid density gauges. Because of grade changes in the tunnel, as well as existing obstructions along the tunnel sidewalls, the open channel carrier pipe was installed in multiple steps in which discrete lengths of pipe were placed at different elevations. In 1997, we extended the carrier pipe to the



CALCULATION DIAGRAM FOR LIQUID LEVEL SYSTEM

a. Differential displacement in each pipe.

b. Integrated displacement in all pipes.

north and to the south. In addition, we added crossover liquid level systems at the northern and southern ends of each carrier pipe assembly to form a closed-loop system. The crossover liquid level systems were installed through existing tunnel crossover passages that extended between the tunnels. The crossover systems allow measurement of the differential movement of the Red Line tunnels and, more important, allow closure of the entire liquid level system to be monitored.

The crossover liquid level systems consist of 25-mm-diameter stainless steel carrier pipe installed beneath the tracks and through the existing cross passages. Two liquid level gauges are connected to the ends of each crossover carrier pipe. These two gauges are also interconnected by a 6-mm-diameter flexible Teflon tubing vent line, which prevents air from entering the crossover systems.

The entire final liquid level system consists of approximately 1,265-m-long, 75-mm-diameter open channel carrier pipe filled to half-diameter with water, and 46 m of 25-mm-diameter carrier tube entirely filled with water. A total of 106 liquid level gauges and 19 liquid density gauges are connected to the system and monitored by the ADAS. Nine independent liquid level systems exist in each tunnel. Each of the first seven is approximately 18 m long, the eighth is approximately 305 m long and the ninth is approximately 213 m long.

The transition between adjacent systems was accomplished by placing two end-located liquid level gauges from two adjacent pipe systems on the same 4.6-m-long concrete section of the Red Line tunnel. It is assumed that the differential vertical movement between these two gauges always equals zero because they are mounted on the same massive concrete section. This assumption allowed us to develop a continuous plot of differential vertical movements along the total system length of 1,310 m in both Red Line tunnels. The system cost $1.8 million, including hardware and installation under those constraints.

All installations were performed by Shannon & Wilson personnel during MBTA non-revenue hours (between 1:30 and 4:30 a.m.). MBTA construction supervisory personnel provided access to the tunnels. Access restrictions and working conditions during system installation were severe and depended on many factors, including MBTA operations and weather conditions.

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PRELIMINARY RESULTS

Each gauge reading refers to an initial value, which we selected after evaluating hourly monitoring data for one week to determine the effects of temperature and tidal changes. The initial value is an average of this weekly data. The hourly monitoring results indicated that many of the gauges measure differential vertical movements directly related to tidal cycles of the water level in the Fort Point Channel. The maximum measured tunnel movement from tidal changes is about 0.125 mm. This response to tidal changes shows that the gauges are actually more sensitive and more accurate than the designers' performance requirements and the manufacturer's specifications.

The first set of initial readings for the system was taken on July 1, 1996. Starting from the middle of August 1996, differential settlement of the Red Line tunnels occurred as a result of adjacent CA/T construction. We measured approximately 7.5 mm of vertical differential settlement in both tunnels. At that time, we decided to extend the system to the north and south. The second set of initial readings for the extended system was taken on Oct. 11, 1997. Since that time, the closure measurement has been used to characterize the overall performance of the system. We found that system closure has varied from 0.1 to 0.5 mm. This is excellent, considering that the system is 1,310 m long and includes 20 individual liquid level systems, 106 liquid level gauges and 19 liquid density gauges.

The liquid level gauges are actually more sensitive and accurate than we anticipated. The open channel carrier pipe design is a major contributor to this excellent performance. The liquid level system is monitoring the safety of the Red Line tunnels during construction, and we expect it to provide an early warning of potential problems.

The liquid level system can be designed and used for precise measurement of differential vertical movements in many types of facilities—tunnels, bridges, dams and other structures. The system can be temporarily or permanently installed on the surface or embedded within a structure. ▼

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