Tensioned Wire System for Monitoring Tunnel Movement

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The Westway Highway Project was designed to extend from the Bulkhead Line of Manhattan roughly 305 m (1,000 ft) into the Hudson River to the Pierhead Line. The roadway was to be constructed over four existing tunnels crossing under the Hudson River to New Jersey. Two Port Authority Trans-Hudson tubes carry passenger trains, and the two tubes of the Holland Tunnel carry vehicular traffic. The tunnels are old, and all have experienced settlement. It was considered essential that tunnel structures be monitored accurately and frequently throughout the estimated 2-year construction period, but the tunnel environments are extremely hostile to monitoring systems. Closing tunnels frequently for extended periods to monitor tunnel movement was unacceptable. Monitoring systems studied in great detail included optical surveys, lasers, and hydraulic pneumatic settlement devices. Serious problems with each of the systems studied could not be resolved. The Engineering Department of the Port Authority of New York and New Jersey developed the Tensioned Wire System, to monitor horizontal and vertical movement in the tunnels. Several prototype systems were designed and installed to demonstrate their feasibility and gain experience. The wire system was capable of measuring horizontal and vertical movements of tunnels to precisions of 0.8 mm (0.03 in.) at 40 locations in 20 min. The Westway Highway Project was terminated a short time before being sent out for bids, and the Tensioned Wire System was never implemented. Although it was not tested under long-term service conditions, its potential for survival was considered to be very good.

In 1984 a combination of environmental concerns and legal actions caused the Westway Highway Project to be terminated a short time before it was sent out for bids. The project was designed to extend from the Bulkhead Line of Manhattan roughly 305 m (1,000 ft) into the Hudson River to the Pierhead Line. The roadway was to be constructed over four existing tunnels crossing under the Hudson River to New Jersey. Two Port Authority Trans-Hudson (PATH) tubes carry passenger trains, and the two tubes of the Holland Tunnel carry vehicular traffic. The PATH tubes were constructed around 1905, and the Holland Tunnel was constructed in 1927.

Previous monitoring of the tunnels' movement by optical surveys indicated that they had all moved laterally and vertically. Tunnel diameters for the PATH tubes are 4.86 m (16 ft) and 5.78 m (19 ft), and the Holland Tunnel tubes are 8.82 m (29 ft) in diameter. The tunnels are in stable ground at the Bulkhead Line, bedrock at the Pierhead Line, and in soft Hudson River silt for most of the tunnel sections in between. The tunnels are bolted ring construction.

Proposed construction of the Westway protective structure over and adjacent to the tunnels presented serious potential for unavoidable lateral and vertical movement of tunnel sections. Excavation of silt above the tunnels could cause buoyant rise, and excavation adjacent to a tunnel could produce lateral movement in the soft silt. Several hundred 2.1-m (7-ft) diameter caissons were to be constructed about 4.6 m (15 ft) from the tunnels. A "blow" during the installation of a caisson could result in a serious loss of support in the silt surrounding the tunnel.

Tunnel movements were to be monitored with sufficient accuracy to lead to early recognition of unfavorable trends and permit prompt application of remedial measures. Monitoring systems were to be installed in each tunnel before the start of any construction to determine normal movements of the tunnels and verify the accuracy and reliability of the monitoring systems.

TUNNEL ENVIRONMENTS AND CONSTRAINTS

The tunnel environments are extremely hostile to monitoring systems. Ventilation fans in the fresh air ducts below the roadways in the Holland Tunnel (where the monitoring points would be installed) force air through the ducts at 40 m/sec (90 mph). Vehicle emissions create acid rain, and debris falls from the roadway scuppers into the ducts. PATH trains push horizontal columns of air ahead of them as they speed through the tunnels with minimum clearance. All tunnels operate 24 h a day, 7 days a week, and service is interrupted only for maintenance and emergencies. The heavy traffic causes vibration, raises dust, and produces constantly changing and variable conditions of moisture and temperature. As shown in Figure 1, the PATH trains fill the tunnels, and working space is very limited. Working conditions in all the tunnels are unfavorable.

The problems associated with installing, reading, and maintaining an accurate and reliable monitoring system that could be read quickly and frequently were formidable. Worker safety, ease of reading, the time required to obtain data and reduce it, and the need to minimize interruption to service were important considerations. The survival of monitoring systems in the tunnels for more than 2 years was another factor that was considered.

MONITORING SYSTEMS STUDIED

The monitoring system was required to measure horizontal and vertical movements of the tunnels at about 40 locations in a 305-m (1,000-ft) long section of each tunnel. Any monitoring system believed to be potentially feasible was studied in detail. The main systems studied are described briefly.

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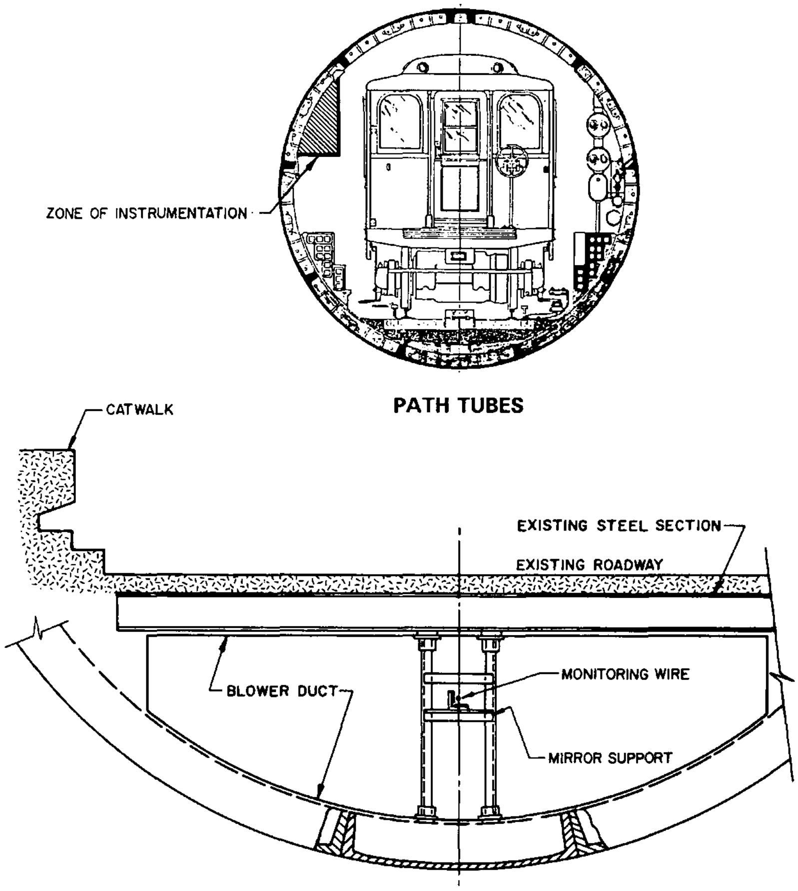

FIGURE 1 Location of instrumentation.

Optical Survey

The optical survey method was important as a backup system to check critical measurements at selected locations, but it was too slow, cumbersome, and limited in accuracy for measurements of tunnel movement on a frequent basis. It had no automatic alarm capability.

Laser System

In 1979 manufacturers of laser equipment believed that suitable equipment could be developed for monitoring 305-m (1,000-ft) lengths of tunnel, but no equipment was available at that time. Unstable moisture and temperature conditions and gradients, vibrations from many sources, dust, smog, and potential damage to workers' eyes were other important problems. After extensive study, laser systems were finally abandoned. Although laser technology today is improved, the problems remain formidable.

Hydraulic-Pneumatic Settlement Device System

The hydraulic-pneumatic settlement device system, which could measure only vertical tunnel movements, was studied extensively. It was abandoned when problems caused by erratic temperature gradients and moving air limited its accuracy and reliability.

Tensioned Wire System

The Tensioned Wire System, to monitor both vertical and horizontal movements of the tunnels, was developed by the Engineering Department of the Port Authority of New York and New Jersey. Measurements of horizontal and vertical movement at 40 monitoring locations could be made in less than 20 min by workers with no special skill or training. The precision of readings could be 0.8 mm (0.03 in.). Data reduction, requiring only basic arithmetic, would be fast and simple. An automatic alarm system, capable of transmitting an electric signal if any tunnel monitoring point moved more than a preset distance, was an important additional feature.

DEVELOPMENT OF TENSIONED WIRE SYSTEM

A prototype of the Tensioned Wire System was installed in the fresh air duct located below the roadway in a 366-m (1,200-ft) section of the Lincoln Tunnel in 1978. The installation was similar to the schematic concept shown in Figure 2. At the

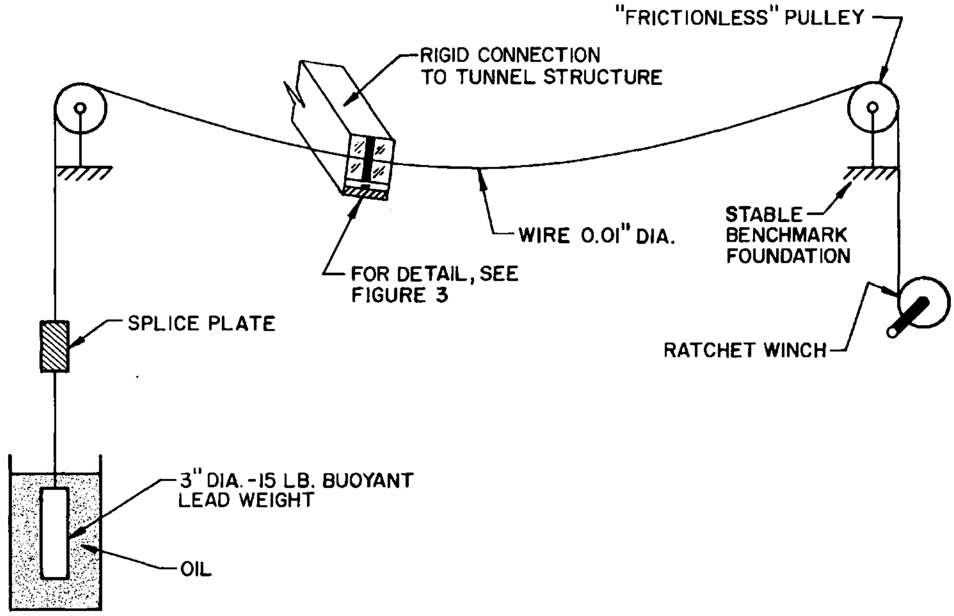

FIGURE 2 **Schematic of basic Tensioned Wire System.**

locations where the monitoring points were attached to the tunnel wall, the maximum headroom clearance was about 760 mm (30 in.). A stainless-steel wire with a diameter of 0.18 mm (0.007 in.) was suspended between two pulleys roughly 366 m (1,200-ft) apart. The maximum sag in the wire was less than 760 mm (30 in.) under a constant tension of 53 N (12 lb). The tensile stress in the wire was over 2 GPa (300 kips/in.^{2}), not far below its breaking strength. A total of 27 monitoring points were installed. The wire had no protection at all, and it survived for 1 month. During that period, it was subjected to the following:

- Wind velocities of 40 m/sec (90 mph) from blower duct fans,
- Corrosive fluids and debris falling from roadway scuppers leading from the roadway drains to the duct,
- Corrosion caused by salts and acid rain from roadway vapors and engine exhaust, and
- Possible tampering by curious individuals.

The wire was broken by a car side mirror that had fallen from a roadway scupper. When the wire was replaced, the new readings agreed with previous results. After the wire had been replaced several times, it was concluded that the wire system was feasible, but the wire would have to be protected in a tunnel environment.

In 1982 a temporary wire system was installed in a 305-m (1,000-ft) long section of one of the PATH tubes. This prototype installation took about 30 min to complete, and it demonstrated the feasibility of the wire system functioning in the limited working space of the PATH tunnels. Design measurements were made at locations of critical clearances. A special wire with a unique combination of strength and corrosion resistance was obtained. The wire diameter was 0.25 mm (0.01 in.), and it was tensioned to 1.4 GPa (200 kips/in.^{2}), about 70 percent of its breaking strength. In the final design, intermediate pulleys (called saddle points) were added at key locations to provide horizontal clearance from obstructions and to accommodate horizontal alignment curves in some of the tunnels.

DESIGN FEATURES

Basic Concept

As shown in Figure 2, a wire suspended under a constant tension between two fixed benchmark points in a tunnel remains in a stable configuration. The winch is used to take up slack during installation, and the "frictionless" pulleys (which are not completely frictionless) maintain a constant tension regardless of temperature changes or lateral movement of benchmark points. When the wire is tensioned and protected, it is unaffected by changes in temperature or any of the other unfavorable conditions in the tunnels. If the fixed and benchmark points do not move (they were anchored in tunnel locations in bedrock or stable ground), the wire location provides a constant reference for observing tunnel movements by measuring distances between the wire and rulers rigidly attached to the tunnel structure at the monitoring points. The frictionless pulleys were to be fully protected and enclosed to minimize the tendency for any slight changes of wire tension to occur. Small rotations of the pulleys at the time of the readings would free up any friction between the wire and pulley and ensure the correct tension in the wire.

Wire Protection

In the final design, the entire system was enclosed. The wire was suspended inside a 102-mm (4-in.) diameter pipe, and the other parts of the system were enclosed within larger pipes. In the PATH tubes, the pipe was designed as a handrail to assist personnel in climbing to safety from the tracks.

Readings

Readings were to be made through glass-sealed openings in the pipe at locations of monitoring points. The wire was to be read on machinists' rules set horizontally and vertically as shown in Figure 3. Future changes in readings would indicate horizontal and vertical movement of the tunnel structure because the wire position would remain stable and constant. Locations and elevations of fixed benchmark points and tunnel monitoring points were to be checked by optical survey.

Obtaining and Processing Data

In the PATH tubes, where trains run on 20-min schedules late at night, a flatcar with 20 workers could be brought to a 305-m (1,000-ft) long section of tunnel. Each individual could read two monitoring points and be back on the work car in less than 15 min. Tunnel movements would be known immediately by comparing results and previous readings. In the Holland Tunnel, readings would be made when the fans could be shut down.

Automatic Alarm

Presetting wires rigidly attached to the tunnel structure a selected distance from the tensioned wire and connecting them to an electric source could achieve an automatic alarm system. Contact between the preset wire and the tensioned wire would trigger an alarm and locate the problem for further checking. This feature was never implemented and tested, but it was believed to be feasible.

CONCLUSIONS

After intensive study lasting several years, the Tensioned Wire System was finally selected as the primary monitoring system for the tunnels. It was the only survivor of all the systems studied. Although the Tensioned Wire System was not a "high-tech" solution, it did work when other methods studied had to be abandoned because of the unfavorable conditions and constraints found in the tunnels. However, there was considerable resistance to accepting the Tensioned Wire System.

The Tensioned Wire System has great flexibility and can be adapted to fit a wide range of conditions and situations not discussed here. At locations where tampering is unlikely, for example, the wire would probably not require any protection. It can also be set up and taken down quickly so that the wire would be in place only when measurements were being taken. It could be a portable system, used on an as-needed basis.

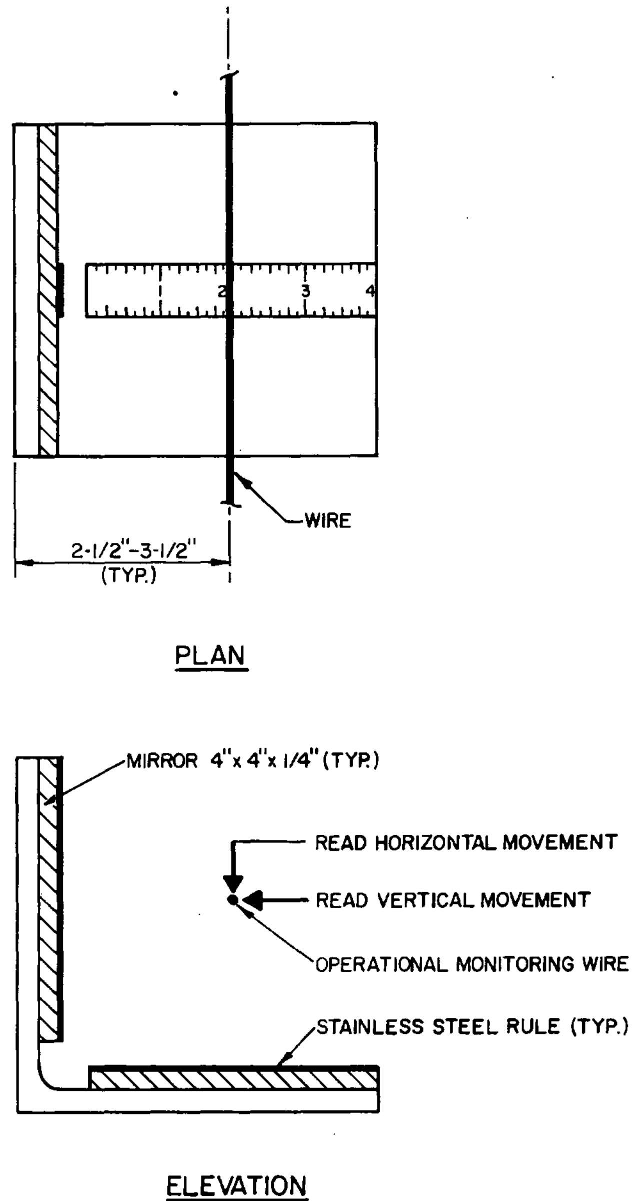

FIGURE 3 Reading horizontal and vertical movements.

The Tensioned Wire System has been patented. Anyone wishing to use the wire system on a project can do so at no charge by requesting written permission from the authors of this paper. Under adverse conditions, the Tensioned Wire System may be the best way to obtain important data.

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