Instrumental Approach

Construction at a water treatment plant in Toronto that has rendered many years of service required assurances that facilities there would experience little or no movement. An extensive monitoring regime incorporated into the project's design and construction helped to ensure that this challenge was met.

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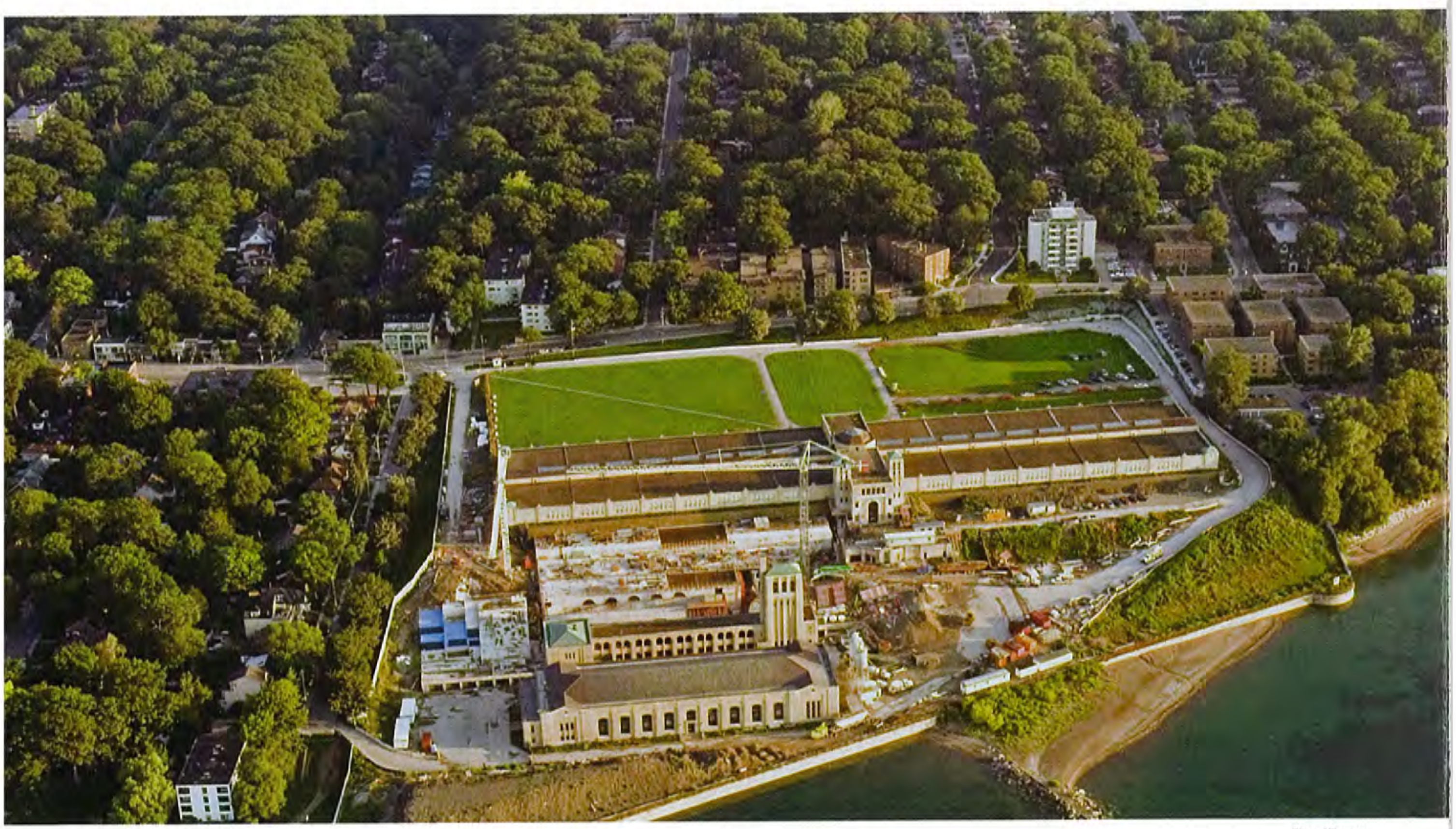

City of Toronto

A series of underground tanks is under construction on the hillside between two structures that form part of Toronto's R.C. Harris Water Treatment Plant, a classic example of art deco architecture declared historically and architecturally valuable by the Ontario Heritage Act. To prevent damage to the structures from construction, a complex monitoring program that includes inclinometers, electrolytic tilt sensors, extensometers, precision and pile target monitoring, load cells, thermistors, and tension-monitoring cables has been designed.

The expansion of Toronto's R.C. Harris Water Treatment Plant highlights ways in which design, construction, and field monitoring can be combined, despite physical impediments at the site, to satisfy stringent requirements regarding building movement during construction. Begun in October 2004, the expansion involves the construction of a residual management facility between two critically sensitive structures at the plant. The new facility will be located underground in two stepped excavations—12 and 10 m deep—that will then be covered to preserve the site's architectural features. Because the filtration plant is a critical component of Toronto's infrastructure, construction of the new facility could not interfere with the plant's operation.

Constructed between 1934 and 1937, the R.C. Harris Water Treatment Plant provides drinking water to more than 2.5 million people in the Toronto metropolitan area.

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First expanded in the 1950s, the facility produces an average of 482,000 m^3/d and has a maximum treatment capacity of 950,000 m^3/d. Perched atop a bluff on the north shore of Lake Ontario, the plant has a commanding presence on the lake's shoreline. A classic example of art deco architecture, it includes structures that have been designated as historically and architecturally valuable under the Ontario Heritage Act, and in 1992 it was named a civil engineering landmark.

A series of underground tanks under construction in the hillside between two existing structures—the filter building and the services building—will be covered to preserve the facility's architectural style. The filter building is positioned at the crest of the hill and the services building is located downslope; the excavation is between the two. Contract documents required two stepped excavations with depths of 12 and 10 m supported by secant walls extending down more than 35 m to rock.

The drilled shafts used to construct the foundations for the underground tanks penetrate a gravel layer with high artesian head. Meanwhile, aquitard soils—those that contain groundwater but cannot transfer that water—above and below the gravel layer contain cobbles and boulders, creating challenging drilling conditions. The presence of sand prompted concerns that drilling might cause excess ground loss below the footings of the two buildings and compromise their structural integrity. Because of the potential for piping, ground loss, and settlement, the risk to the existing buildings and plant was considered high.

Concerns regarding potential movements at an existing expansion joint within the plant's potable water tanks prompted the City of Toronto's design engineer in charge of contract administration—CH2M HILL, of Englewood, Colorado—to limit the allowable lateral deflection of one excavation support wall to 4 mm. A comprehensive monitoring plan was implemented that included inclinometers, electrolytic tilt sensors (also called electrolevels), extensometers, precision and pile target monitoring, load cells, thermistors, and SMART (stretch measurement to assess reinforcement tension) cables. Over the course of several weeks, baseline readings were obtained from all instruments to establish allowable movement criteria and to determine if the mandated limits were attainable.

The design/build team consists of the specialty deep foundation construction company Deep Foundation Contractors, Inc., of Toronto, and the shoring designers Isherwood Associates, of Mississauga, Ontario. After hiring Monir Precision Monitoring, also of Mississauga, to conduct monitoring at the site, the team crafted an alternative design that resulted in significant savings over the original concept. The new concept featured interlocked continuous flight auger shafts with three levels of tieback soil anchors on the critical north-side earth retention wall between

Table 1 Monitoring Locations and Frequencies*

Instrumentation	Number of units	Location	Reading frequency	Baseline requirement
Survey benchmarks	8	Outside zone of influence	Twice weekly	Prior to drilled shaft installation
Surface monitoring point, type 1	135	2 per pile, 43 on buildings	Twice weekly	Prior to drilled shaft installation, except for piles
Surface monitoring point, type 2	46	In three arrays	Twice weekly	When exposed
Inclinometers	10	Piles	Twice weekly	Prior to excavation
Thermistor strings	5	Secant walls	Twice weekly	As available
Piezometers	5	Outside excavation	Twice weekly	Prior to drilled shaft installation
Electrolevels	5	Filter building	Daily	Prior to excavation
Electrolevels	4	Services building	Daily	Prior to excavation
Strain gauges	18–27	Struts	Daily	As struts become available
Vibration monitoring	—	—	Twice weekly	At start of each new operation and then two shifts per week

*Type 1 surface monitoring points measured settlement and horizontal displacement. Type 2 surface monitoring points measured settlement only.

the filter building and the excavation (see the figure at the top of page 68). The design was optimized to minimize movement along a critical expansion joint between the filter building's south-face footing and the tank slab. With extensive analyses performed using finite layer analysis of consolidation (FLAC) methods, the shoring engineers were able to predict movements at each stage of the excavation. Monitoring the movements and comparing them with the FLAC predictions enabled the team to assess the need for design or methodology modifications during construction. Because of its willingness to commit itself to an extensive monitoring program to justify the optimized design, the contractor was able to satisfy the owner's objectives with a cost-effective solution.

Contract documents prepared by the owner's representative dictated the monitoring locations as well as allowable vertical and lateral movements for the neighboring structures and each region of the excavation support. Furthermore, limited differential displacement criteria were established for each structure and region. Table 1 summarizes the specified monitoring locations and frequencies. Table 2 summarizes the specified review and alert levels at several of the monitoring locations. (A general layout of the monitoring points and equipment is shown in the figure on page 69.)

Generally, project participants felt that construction could be conducted without exceeding the allowable movement criteria. However, the lateral movement limits set for the filter building and the 1,200 mm diameter concrete tunnels used for conveying and discharging water at the west side of the excavation were considered very demanding at respectively 4 and 10 mm.

After holding several meetings, project participants determined that the owner's representative was, in fact, less concerned about the filter building's overall lateral movement than about the potential for differential movements across the building's expansion joint between the south exterior wall footing and the tank base slab beyond (see the figure opposite).

Once the key issue was determined, the project's design, analysis, and monitoring programs were adjusted to focus

Table 2 Typical Review and Alert Levels

Location	Level
Cofferdam walls:	
Total vertical movement	25 mm
Relative vertical deflection across a length of 20 m	12 mm
Maximum horizontal movement at elevation 86.2 m above sea level	4 mm
Alert level horizontal deflection	18 mm
Review level horizontal deflection	12 mm
Peak particle velocity at south face of filter building	5 mm/s
Filter building:	
Total vertical movement	25 mm
Relative vertical deflection across a length of 20 m	12 mm
Maximum horizontal movement at elevation 86.2 m above sea level	4 mm
Alert level horizontal deflection	18 mm
Review level horizontal deflection	12 mm
Peak particle velocity at south face of filter building	5 mm/s
Tunnels and conduits:	
Total allowable vertical movement	25 mm
Relative vertical deflection across a length of 20 m	15 mm
Maximum horizontal movement	10 mm
Alert level for settlement	18 mm
Review level for settlement	12 mm
Peak particle velocity at south face of filter building	5 mm/s

more on the potential for movement at the construction joint at the bottom of the tank. The design, then, concentrated on reducing differential lateral movements of the filter building, and the monitoring was modified by adding direct measurements across the critical joint, allowing for more lenient movement criteria.

Extensive FLAC analyses carried out by the shoring engineers indicated that the filter building's movements would be elastic and would be distributed up to 50 m back from the structure's south footing. Therefore, the amount of movement at the shoring or the filter building walls would not necessarily indicate differential movement across the expansion joint.

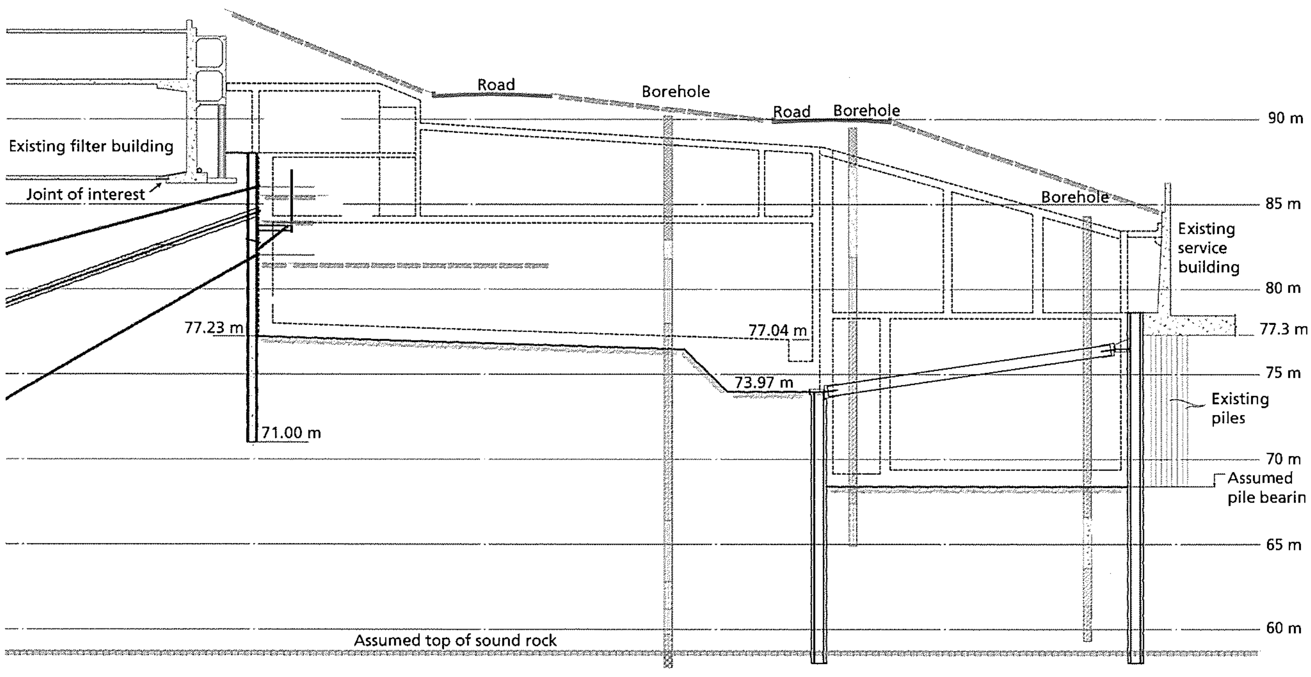
To monitor the most critical area precisely, a total of four vibrating-wire extensometers were installed within the filter building tanks. At two locations, two extensometers were installed so as to span the expansion joint between the south footing and the base slab. At each location, one extensometer was used to monitor movements directly across the joint and the other was used to monitor movements between the footing and the wall of the flow control structure located in the middle of the tank, a distance of more than 5 m.

To monitor movement across the critical joint, two vibrating-wire extensometers were attached to telescoping 1,500 mm diameter aluminum tubes that were anchored into the tank walls and supported by the columns. Extensometers equipped with thermistors measured changes in water temperature to distinguish between movements caused by construction and movements caused by temperature fluctuation in the tanks.

The logistics proved to be intricate because of the short installation window of 48 hours—the maximum amount of time that the City of Toronto could afford to have the tanks out of service—and the locations where the instruments were to be installed. The tanks, which were decommissioned strictly for this installation, were to be refilled with treated potable water after the installation. Therefore, it was imperative that all steps related to the installation be precisely planned and coordinated. For example, any materials and equipment entering the tanks had to be made with approved materials—stainless steel or aluminum—and sanitized. Checklists and inventory counts were used to ensure that tools were not left behind after the installation. In this respect, the checklists provided in John Dunnicliff and Gordon E. Green's *Geotechnical Instrumentation for Monitoring Field Performance* (Wiley, 1988) proved invaluable as a planning tool.

Most readings were taken at the specified frequencies. However, on several occasions reading frequencies were increased at particular instruments or locations to monitor an area of concern more thoroughly.

Cross Section



Isherwood Associates

Because of damage during construction, surveying points atop the tunnels and two piezometers were reinstalled several times. In view of the significant construction activity, the tight spaces, and the amount of instrumentation throughout the site, a relatively insignificant number of monitoring points and instruments were damaged.

In lieu of one technician remaining on-site full-time to perform all monitoring, experts read the instruments pertaining to their specialties. For example, in a typical week the survey specialist would make two site visits to read the survey targets; the inclinometer technician would make two site visits to read the inclinometers, piezometers, and any other manally read instruments; and a vibration monitoring specialist would perform such monitoring when required. This option proved to be an effective solution for minimizing risks, as each instrument was read by the appropriate specialist.

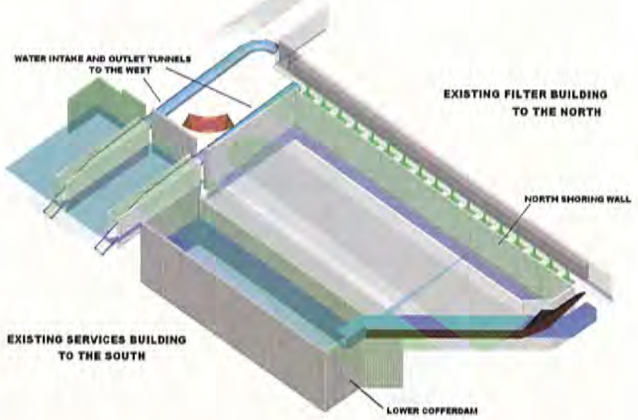
Readings were collected remotely from the electrolevels, strain gauges, and vibrating-wire extensometers via data loggers equipped with dial-up modems. An on-site office was set up within a contractor's trailer so that manually collected monitoring data could be processed by a technician before he or she left the site. In this way, should a questionable set of data arise during processing, the technician would not have to return to the site to complete a control reading to verify the data. This approach also enabled the technician to compare readings with the review and alert levels, ensuring that all parties named in the monitoring action plan were notified in a timely manner if a particular level was reached.

Data were reported and distributed in both tabular and graphical formats, and care was taken to ensure that movements and trends were clearly depicted in the graphical format. Within a couple of hours of a report's completion, the data were distributed via a password-protected file transfer protocol (FTP) server that was accessible to interested stakeholders. Throughout construction, monitoring results were frequently compared with the predicted movements to ensure that the design and ensuing construction met the design/build team's expectations.

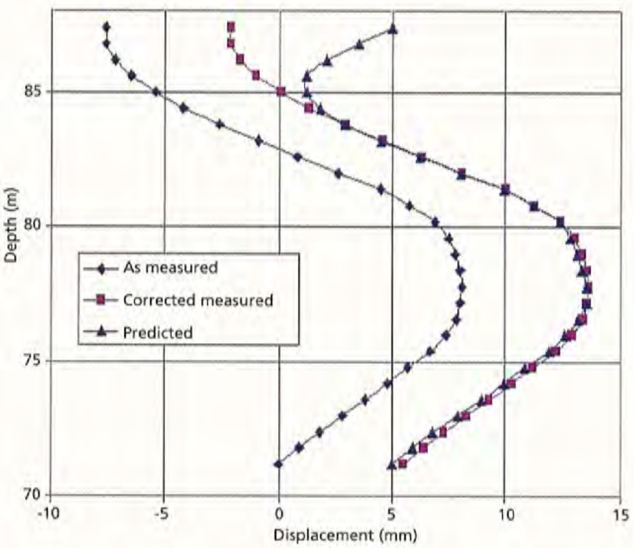
The performance of the critical north shoring wall adjacent to the filter building was monitored by a succession of four inclinometers, precision survey points at two locations on each soldier pile within the drilled shafts, four electrolevels, tieback load cells, and several SMART cables. Because they provided the most critical information regarding the shoring wall and building movements throughout the site, the inclinometers, the precision survey points, and the vibrating-wire extensometers proved to be the monitoring system's most vital elements.

Cross-checking and integrating all of the data into the overall monitoring results provided a valuable tool for observing how each monitoring instrument interacted with its counterparts. For example, the inclinometer traces—that is, inclinometer movements projected in graph form on this page—were corrected by adjusting the top-of-wall movement to the results of the precision survey, which provided the as-measured and adjusted inclinometer displacements as well as the displacements predicted by the FLAC analysis for the north shoring wall.

3-D Image of Stepped Excavation



Actual Measured versus Predicted Results For North Shoring Wall



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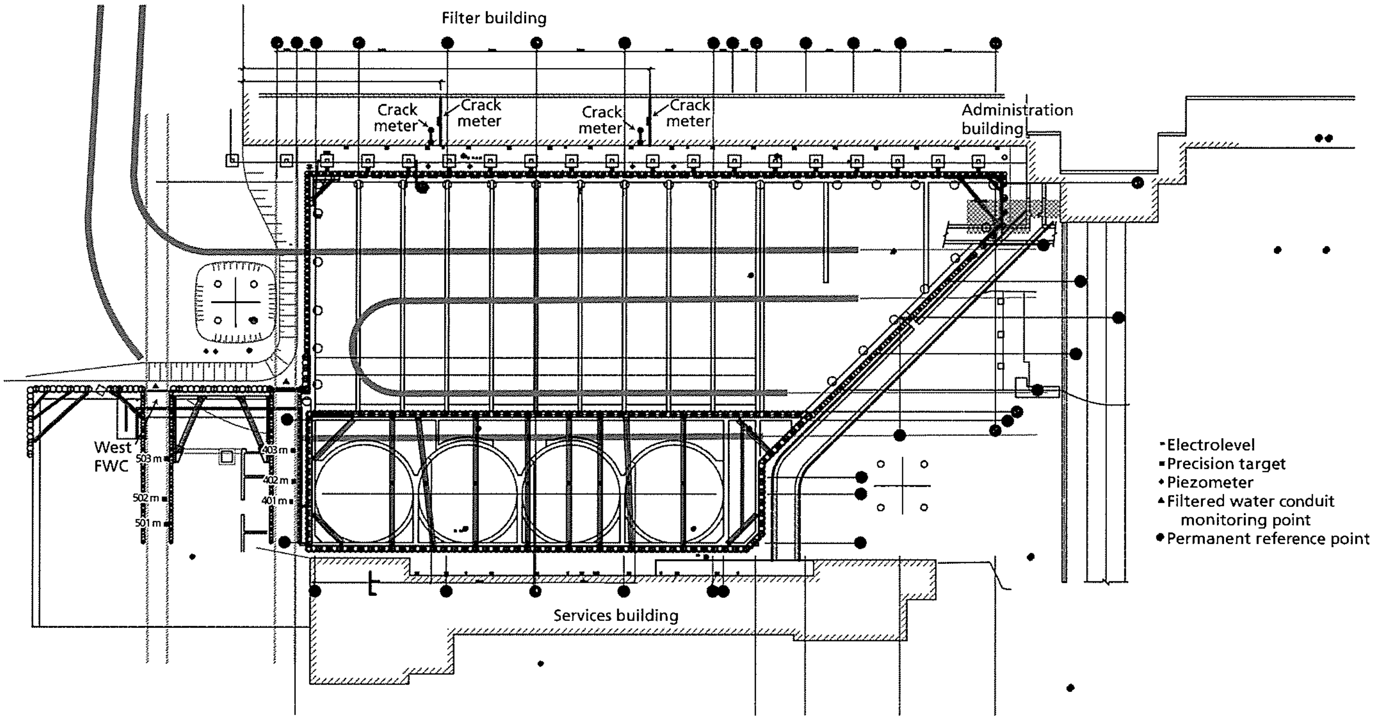
Movements measured by the inclinometers on piles that form part of the shafts built for the foundation walls indicated that the upper portions of the piles were pulling "out of site," that is, toward the filter building, while the toe of the inclinometers remained stationary. Inclinometer measurements are predicated on the assumption that the toe of the inclinometer penetrates below the active soil mass. Based on data obtained by cross-checking precision surveys at the tops of the piles and at their midpoints, the inclinometer movements could be adjusted to these accurate baselines. The resulting corrected curve indicated that the tops of the piles were pulled slightly out of site, by 1.5 mm. The toe of

Diagram of Monitoring Site Plan



Monir Precision Monitoring

the pile moved "into site," or away from the filter building, approximately 5.5 mm. These observed movements differed from the prediction of the FLAC analyses that the pile would move toward the excavation at the top. However, the predicted pile movements below the top tieback level closely matched the observed movements.

The north shoring wall's movements consistently matched the movements and loads predicted by the FLAC analyses, including the overall magnitude, deflected shape, and toe deflection. The tieback loads, monitored via liftoff tests and permanent load cells, sustained loads that consistently matched the jacked-in and predicted loads. (Liftoff tests are typically used throughout construction to confirm that the load remains consistent in a shoring element.) Meanwhile, the electrolevels installed on the neighboring structures indicated negligible differential movements or rotation, again in keeping with the FLAC prediction. The vibrating-wire extensometers revealed no discernible movement across the joint-monitoring apparatus.

This project illustrates how monitoring the performance of excavation support systems can be a vital component of a complex project when geotechnical observations and instrumentation are used during construction to adjust designs in accordance with field conditions. The support system was expressly designed to address risk at potentially challenging locations. The system's overall performance was monitored throughout construction by measuring pile and building movement. Moreover, the monitoring made it possible to confirm design assumptions early in the construction process.

Extensometers installed within the potable water tanks were of paramount importance in monitoring joint movements at the critical junction between the filter building's south-face footing and the slab beyond. Instantaneous monitoring in the 12 months after the installation of the extensometers showed negligible movements across the joint at the filter building's south-face footing, while the accompanying instrumentation detected total construction-related horizontal movements of 6 to 10 mm at the same location. These findings gave the client the assurance necessary to modify the allowable lateral deflection.

Construction associated with the expansion of the R.C. Harris Water Treatment Plant is expected to be complete by year's end. The design/build team's approach of analyzing areas of concern, using models to predict behavior at these areas, and then monitoring the areas to confirm design assumptions and performance worked well to reduce risk and construction costs considerably. The design, analysis, installation, and monitoring of the project met the owner's needs for a cost-effective solution. ■

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