# Monitoring a heritage building restoration project with geotechnical instrumentation

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## Introduction

2017 marks the 150$^{th}$ anniversary of the Canadian Confederation. Amidst the preparations for the celebrations, infrastructure projects have been undertaken, including major work to modernize, both structurally and esthetically, the 150-year old West Block Building while maintaining its heritage appearance (depicted in Figure 1). The project required extensive monitoring with geotechnical instrumentation. The structural work requiring instrumentation had three phases:

1. Backfilling of abandoned tunnels
2. Excavation of the inside of the north wing to add new basement floors
3. Excavation of the inner courtyard to add new basement floors

An overview will be provided of what to be aware of regarding instrumentation, and some issues that arise from working in a demolition-related project. Additionally, there will be specific examples regarding the effects of temperature and the importance obtaining and generating proper baselines.

## Settlement system

### *Purpose and description of instruments*

During Phase 1, tunnels running under the building were reinforced and backfilled. Because this phase could induce significant differential settlement, a highly sensitive settlement measurement system was installed (Geokon 4675). In this system, the sensors are connected to each other with liquid-filled flexible tubing. Each sensor measures the liquid level within its housing. The liquid level difference with respect to a reference sensor is equal to the differential settlement value

*Figure 1 Picture of Parliament Hill's West Block*

*Sources of inaccuracy*

Temperature variations create challenges. Since these systems measure differential liquid levels, temperature changes at one part of the system will alter the specific gravity of the liquid locally, inducing inaccurate readings.

In addition to temperature, the presence of air bubbles can severely impact the quality of measurements. Indeed, air being a compressible fluid, it can "dampen" shifts in position of the water containers and yielding unreliable. One-point liquid-based settlement systems can be back-pressured to push out the bubbles but it is not feasible in this system given that there are several measurement locations on the same line and that bubbles can be trapped in localised "kinks."

*Installation*

There are several limitations that were to be overcome during installation. The line and sensors had to be installed in cramped spaces, around beams, inside doorframes and so on. The complex arrangement in the building made it impossible to avoid curves that could trap air bubbles in the liquid, so the line had to be filled before being attached to the wall. However, filling the line before running it makes installation even more demanding because of the added weight.

To minimize inaccuracy due to temperature changes in the liquid and to have access to the full measurement range, these settlement measurement systems also require that the sensors be at the same elevation, within 10 mm of each other. While this is reasonably easy to achieve on a single long wall or a tunnel, it is much more difficult where there is little to no line of sight for use of laser levels, obstruction rendered the use of water levels arduous, and where floors and ceilings are either absent or uneven. We modeled the effect of lowering or raising each liquid container with respect to its sensor before we were able to position each of them at the right height. Moving any one of the reservoirs up or down would have an effect on the readings of the other measurement points.

*Results*

We were asked to place some of the sensors outdoors, where the sun would heat up the sensor housing, yielding unreliable data during daytime (i.e. sunlight would heat one part of the line). This can be seen in Figure 2, where measurements (blue curve) shift rapidly from daytime to nighttime as it follows air temperature (orange curve). It can also be seen that perceived settlement changes over months in such a way that is difficult to specifically attribute to real differential shifting or to temperature effects. There is a correlation between the two curves, but the exact relation between the two is unknown. In addition to these concerns, workers would occasionally operate space heaters in the vicinity of the instruments without telling anyone, inducing false readings of shifts.

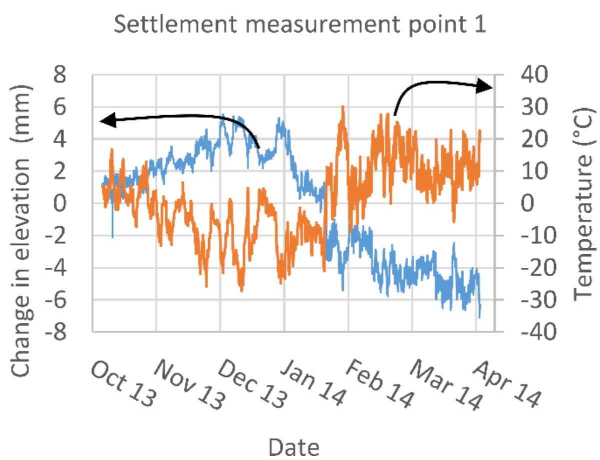


*Figure 2 Differential settlement measurement of an outdoor wall (blue) and measured temperatures (orange)*

One of the liquid lines was accidently damaged and this has been a recurring theme throughout this project, an expected outcome of instrumenting a demolition project. Though a cut can be fixed, it makes comparison of data before and after the break difficult to perform.

*Recommendations for future use*

If there is critical safety and data resting on the settlement system, it is crucial to protect the lines and they should be put entirely out of reach or be protected by a conduit.

Ideally, settlement systems such as these need to be installed in temperature-controlled environment to provide best accuracy.

If the system cannot be back-pressured, it is a better practice to fill it with liquid before installation and make sure no air bubbles remain in the system.

Using laser levels is the best approach to install sensors at the right height when the conditions permit it.

## Multi-point borehole extensometers (MPBX)

*Purpose and description of instruments*

Over the course of phases (2) and (3), instruments such as vibrating wire MPBX (Geokon model 1280) and in-place inclinometers were routinely used to follow the effects of excavation both inside and outside the building. They provided independent data and complemented measurements from settlement systems.

*Sources of inaccuracy*

MPBX are fairly robust instruments that do not have many sources of inaccuracy once they are properly installed. The main source of inaccuracy for this type of instrument would be caused by a mismatch between the soil and the grout's hardness.

Vibrating wire MPBX, despite being tedious to install properly when compared to other solutions, were chosen because we would have a single type for all instruments. This gave us the opportunity to greatly reduce cabling and to facilitate integration into the dataloggers.

Given the long cabling distances in this project, using vibrating wire instruments sidesteps the issues of voltage drops that occur with potentiometer-based MPBX.

*Installation*

In this project, the MPBX were installed directly into the bedrock and there was very little risk of using an improper (too soft) grout mix.

*Results*

This project showed that confidence in the instruments and their reliability can prove critical. Indeed, every MPBX installed in this project gave nearly-constant and consistent measurements over months. In October 2014, the measured values of one MPBX jumped to more than 5 mm, above the alarm threshold (figure 3 (a)). A rapid investigation found that a worker had excavated just beyond the planned limit and hit the head of the instrument.

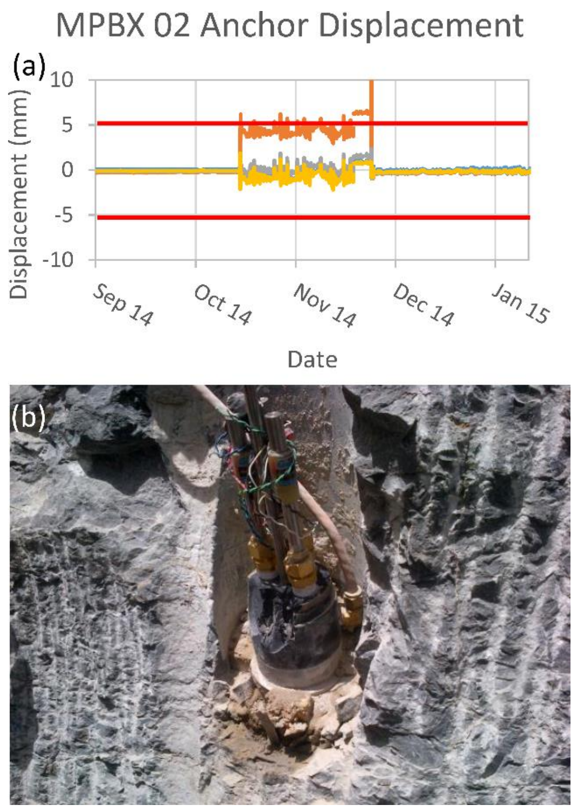


*Figure 3 (a) Anchor displacement of a damaged MPBX (b) Photograph of the head of a damaged MPBX)*

Relying on redundancy and historical data, the engineers were confident enough in the instrument and in the redundancy we had implemented to not immediately stop work despite going against their internal processes.

Damage to the head occurred on a few occasions, an example of which is depicted in the photograph of figure 3 (b). It can be seen that, in this case, half the head of the instrument was torn off. The simple fact that the instrument was nearly destroyed shows their vulnerability in a demolition and restoration project.

*Recommendations for future use*

Performing long term-monitoring to build confidence in the instrument and the measurements is strongly recommended whenever possible. This confidence helps the engineers to make the right decision when unexpected jumps or breaks in the data occur.

## Tiltbeams

*Purpose and description of instruments*

Vulnerable walls were monitored with vibrating wire tiltbeams (Geokon model 6350). Though tiltmeters are commonly used in structural health monitoring, tiltbeams were selected because they were to be installed on masonry walls which can flex due to their mortar joints. Using long (2 m) tiltbeams averages out localized tilts and provides a better image of the behaviour of the walls.

Vibrating wire tiltbeams were selected over electrolytic or MEMS sensors, two other common types of tiltmeters. First, they are less sensitive to temperature effects than electrolytic tiltmeters. Second, integration is facilitated by using a single signal types and by requiring very little power over long distances.

*Sources of inaccuracy*

Temperature-induced errors are the main sources of inaccuracy in this type of instrument. First, temperature affect the reading itself, but this can be corrected to an extent with proper calibration curves. Second, temperature can have an effect the monitored structure and induce real local tilt, often hours after air temperature (*i.e.* the temperature measured by the on-board thermometer) has changed.

*Installation*

For phase (2) and (3), effects of the excavations on the walls were monitored with tiltbeams. Like MPBX, vibrating wire tiltbeams are robust instruments that can be relied upon over long periods of time provided that they are correctly used. Avoiding exposure to sunlight is often recommended as local heating of the structure can induce a small amount of tilt from local sensor and structure deformation. Putting tiltbeams in the shade is not always possible since the outer walls of a building are often more accessible.

*Results*

Measuring variations over weeks or months before work starts can prevent a lot of head scratching because the effect sunlight on the system can be quantified before work begins. The graph in figure 4 shows the effect of temperature and sunlight on tilt measurements for a single tiltbeam in the inner courtyard. From April to December 2014, the measured tilt variation (blue curve), with respect to an initial measurement (blue curve) steadily decreased as temperatures went down (orange curve). Starting in the spring of 2015 values remained low while the temperature increased again. It was impossible to accurately measure the value of tilt until temperatures had climbed back to as high as the initial value. Hour-to-hour comparisons, when temperatures are similar, should give smooth increases and decreases that are repeated day after day. Any sharp or fast change might indicate a blow to the instrument or an actual shift in the wall. Slow and long term tilting can be difficult to detect without a proper base line.

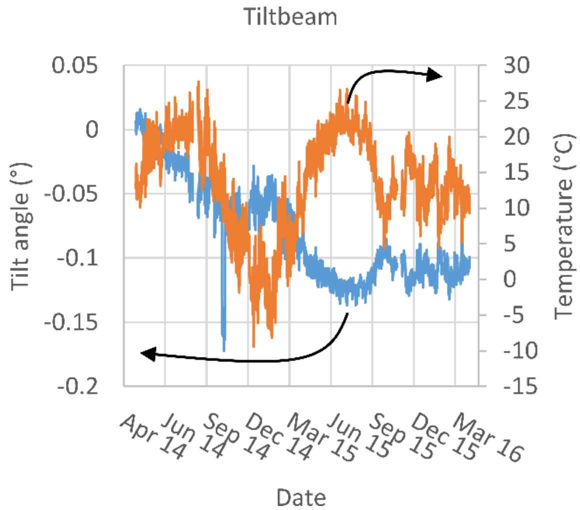


*Figure 4 Tilt angle over time (blue) and temperature (orange)*

*Recommendations for future use*

Installing the tiltmeters indoors or in the shade, though often not possible, can improve the quality of long-term measurements.

In addition to this, when monitoring an already existing structure, a long enough baseline will allow engineers to work out the relationship between temperature and tilt and thus enable the analysis of all subsequent data acquired during the project. In short, baselines are a simple but often overlooked method of improving the reliability of instruments such as tiltbeams and MPBX.

There are several points to take into consideration when choosing between competing technology when choosing an instrument, such as signal type, accuracy, reliability and temperature-dependence.

## Conclusion

In conclusion, restoration of Parliament Hill's West Block is an unusual project for geotechnical instrumentation. In a demolition and restoration project, instruments are constantly put at risk. Communications cables, fluid lines and instruments heads can all be damaged. It is therefore critical to protect the cable and lines, use reliable and trustworthy instruments, plan for redundancy and perform long-term baselines. Applying these measures to any project, and to restoration projects in particular, will greatly improve any monitoring in restoration-related projects.

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