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An Overview of Structural Health Monitoring of the Centre Block in Ottawa During Ongoing Structural Rehabilitation

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ABSTRACT

Structural health monitoring plays a crucial role in the success of a project. This is particularly the case in a project as complex as the Centre Block Rehabilitation (CBR) project, a major rehabilitation of one of Canada's most prominent heritage masonry buildings. The monitoring specifications, layouts of monitors, monitoring thresholds, data processing interfaces and other relevant information gathered from projects previously undertaken across North America, Europe and Australasia were studied to inform the design of CBR's structural health monitoring program. The CBR project includes a deep excavation under the existing CB building, a significantly large masonry structure, in close proximity to the Peace Tower (PT), a 92-metre-tall concrete/masonry structure. Ongoing construction activities such as blasting for rock removal, piling, drilling and others can lead to ground movement, and local and global displacement and rotation of the building. Monitoring of the CB building and the PT through the use of sensitive equipment, strategically placed, is critical to help understand the effects of vibration & settlement on the masonry building structures. Stringent threshold values for movement and vibration were established due to the heritage value of the buildings, which in turn required innovative monitoring equipment such as liquid level systems, robotic total stations, vibration monitors and others. This paper highlights key lessons learned from monitoring strategies of a heritage masonry structure, types of equipment used, the different challenges encountered, and the mitigation techniques adopted for local and global monitoring for the CBR project.

KEYWORDS

Structural health monitoring, data processing, masonry structure, construction activities, threshold values, innovative monitoring equipment, lessons learned.

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INTRODUCTION

Many iconic heritage structures around the world are made of masonry that require special attention during repair and restoration due to heterogeneous property of masonry unlike reinforced concrete. Structural Health Monitoring (SHM) is critical for the successful construction and ongoing maintenance of these structures and complex heritage masonry infrastructure projects. SHM utilizes various types of sensors to monitor movements such as displacement, tilt, settlement, etc., and also serves as an early warning system, enabling course correction and ensuring uninterrupted construction activities. Accurate structural health assessment requires placing sensors at appropriate locations which is critical for long-term continuous monitoring. This helps to establish a baseline for each parameter and is essential for assessing health of the structure/structural component against predefined thresholds that had been set up from previously undertaken projects. [1][2]

Real-time monitoring of structural parameters is crucial for all stakeholders, including clients, contractors, and consultants, to make informed decisions during construction. As masonry materials deteriorate over time, they pose significant risks to structural integrity, potentially leading to collapses such as the San Marco belltower in Venice and the Civic Tower of Pavia. Earthquakes and other events can also cause substantial damage to the existing structures leading to partially or complete collapse of the structure. Heritage towers, often made of masonry alongside added composite mixtures with addition or substitution of structural members, are difficult to estimate local and global behaviour. Researchers often use non-destructive techniques to study these structures' local and global behaviour against any accidental load. [3][4][5]

Structures in extreme climatic conditions, with significant daily and seasonal temperature variations, are analysed for their global behavior under varying ambient conditions. Researchers use temperature-based correlation analysis to determine if a meaningful relationship exists between temperature and the measured parameter. Temperature induced behavior depends on material properties, geometry, and structural complexity. To study anomalies in structural response, temperature induced behavior is required be eliminated. Mathematical models provide a set of equations which illustrate a relationship between ambient temperature and the measured values acquired from a structural health monitoring system. [6][7]

In most masonry rehabilitation sites, SHM systems are employed to assess local and global behavior during various phases of work, such as renovating masonry columns/walls, drilling, piling, slab demolition, and load transfer. Previously performed studies indicate that these systems consist of sensors, a data processing system and a data management system. These combined systems aim to provide reliable health status information for structural safety. [8]

CENTRE BLOCK PROJECT

Centre Block (CB) is the pre-eminent building within the Canadian Parliamentary Precinct. It is a historical structure which includes the House of Commons, Senate chambers, and the Library of Parliament. The Peace Tower (PT) is an approximately 92 m tall clock tower, situated on CB's central axis. CB is currently undergoing its most extensive rehabilitation since its construction almost 100 years ago. The Centre Block Rehabilitation (CBR) project involves restoring much of its architectural and heritage elements and upgrading the structure for seismic resilience. The seismic upgrade strategy includes placing the entire CB and PT on base isolators which includes a significant load transfer process and a construction of a raft above the isolation plane, clamped onto the PT piers with post-tensioning bars. Additionally, a below-grade Parliament Welcome Centre (PWC) is being constructed immediately south of the CB, that began in August 2020. The design of the expansion, conservation, and rehabilitation of CB and PT is led by CENTRUS, WSP-HOK joint venture. [9]

Historical records indicate that the stones used to build the Parliament Buildings, including the CB complex, were mined from various quarries in Canada, United States, and Europe. CB was reconstructed between 1916 and 1922 after a massive fire destroyed the original building. It was rebuilt as a 6-story steel-reinforced stone building, approximately 143 m long and 84 m deep. Since then, the building, including the clock tower, has undergone multiple repairs and renovations to strengthen the infrastructure and readjust interior spaces. [10]

MONITORING STRATEGY

The Building Health Monitoring Program (BHMP) for the CBR project utilizes various sensors to measure parameters such as displacement, settlement, tilt etc., as well as ambient conditions like temperature, humidity, etc. CENTRUS BHMP stores and sends notifications to all parties involved whenever current data exceeds the predefined threshold through a cloud-based Data Management System (DMS). The DMS visualizes data coming from the sensors and can plot different types of charts allowing for data analysis. This is important for assessing data independently and carefully assessing the situation on site to identify the reason for any exceedances. There are two different predefined exceedance limits are for each sensor, Review Level and Alert Level. Review limit is used to notify everyone that sensor is approaching alert limit and corrective actions should be used to avoid reaching the alert limit. Alert limit is to inform everyone that damage could have occurred to the structure. If an exceedance is reached, it is analysed to determine if it was a false alert such as a sensor malfunction or if the sensor was physically struck. If the exceedances are deemed to be legitimate (real movement) a joint site-investigation is organized by all the parties involved for physical inspection of the area, and to discuss the future course of actions. This paper presents different sensor systems and data they have collected over the past year.

Displacement Monitoring System

Displacement monitoring system is crucial for tracking member displacements at critical locations within the project. It provides critical information about joint locations and checks relative movement between masonry piers. In the CBR project, displacement monitoring system measures two key parameters: (a) joint movements at locations with important heritage components using digital Joint Meters, and (b) laser-based distances between piers to measure spreading of the pier legs using Laser Distance Meters.

Joint Meter

Joint Meters measure the distance between two joints to detect any relative movement. This continuous monitoring system collects displacement data every six hours. Review Level and Alert Level notifications are sent when displacement records reach ±1 mm and ±2 mm respectively. In the CBR project, three Joint Meters are installed at different arch locations to monitor movements. The data obtained are shown in Figure 1.

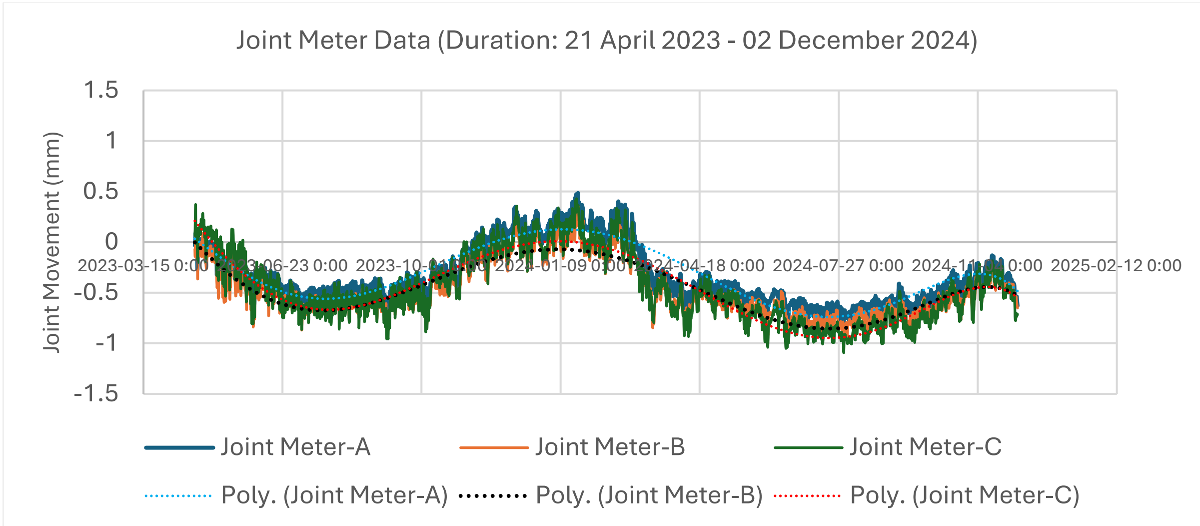


Figure 1: Joint Meter data

Figure 1 indicates some amount seasonality in the data-trend, thus correlation between ambient temperature and Joint Meter data is examined and presented in Figure 2.

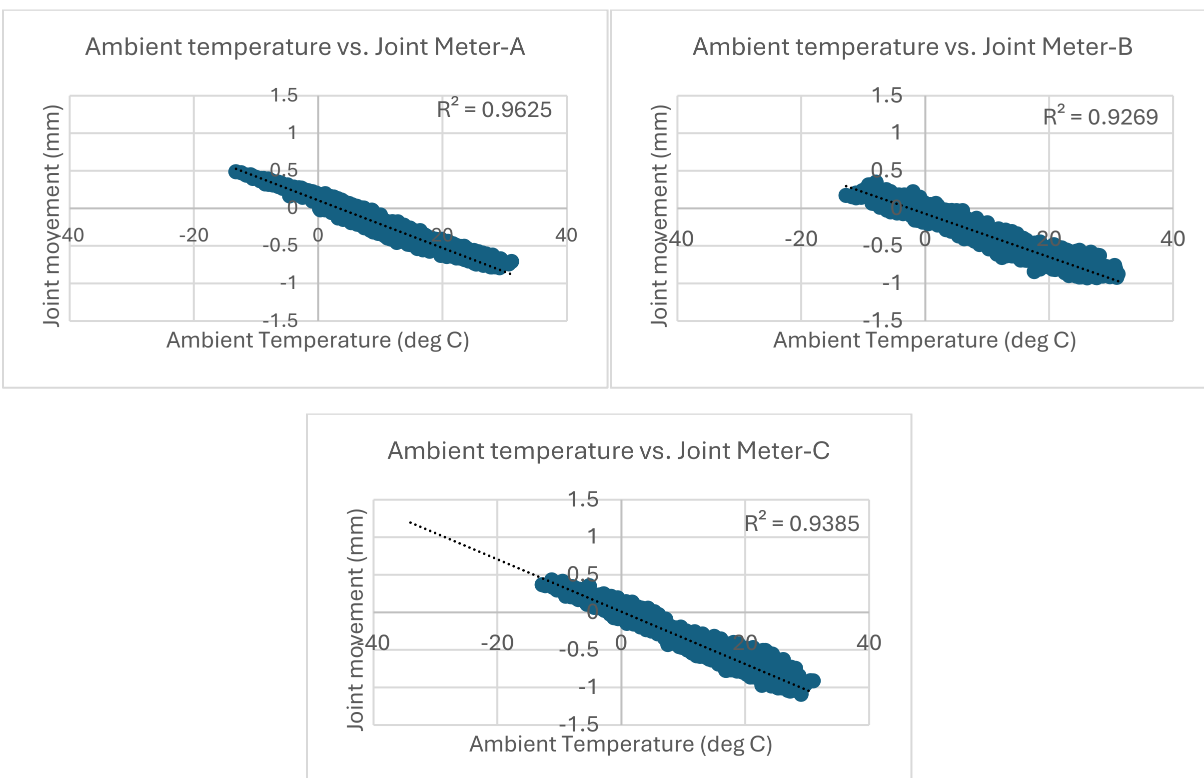


Figure 2: Ambient temperature vs. Joint Meter data (R^2: Correlation coefficient)

Figure 2 indicates a strong correlation between ambient temperature and Joint Meter data, with estimated correlation coefficient value (R^2) exceeding 0.90. To estimate joint movement caused by construction activities, the temperature effect on the Joint Meter data must be removed. By applying linear regression, a regression equation is derived for each dataset. Using ambient temperature values, temperature-driven joint movement values are calculated and subtracted from the original dataset. Figure 3 illustrates the joint movements related to construction activities. Maximum movement of 0.7 mm is observed due to construction activities in the past year as shown in the Figure 3.

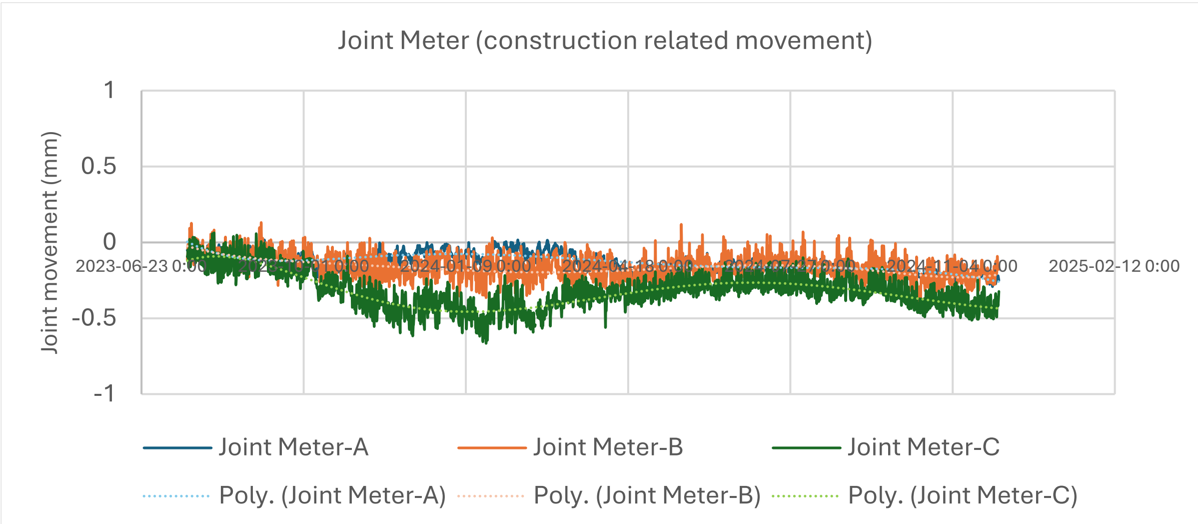


Figure 3: Construction related joint movements

A.2 Laser Distance Meter

Laser Distance Meters use laser beams to measure the distance between two relatively stable points, ensuring the distance remains constant and immediately notify when it changes. This continuous monitoring system collects distance data every six hours and Review Level and Alert Level notifications are sent when distance records reach ±2 mm and ±3 mm respectively. Two Laser Distance Meters are installed to measure diagonal displacements between four masonry columns in the structure. Data collected from these instruments are presented in Figure 4.

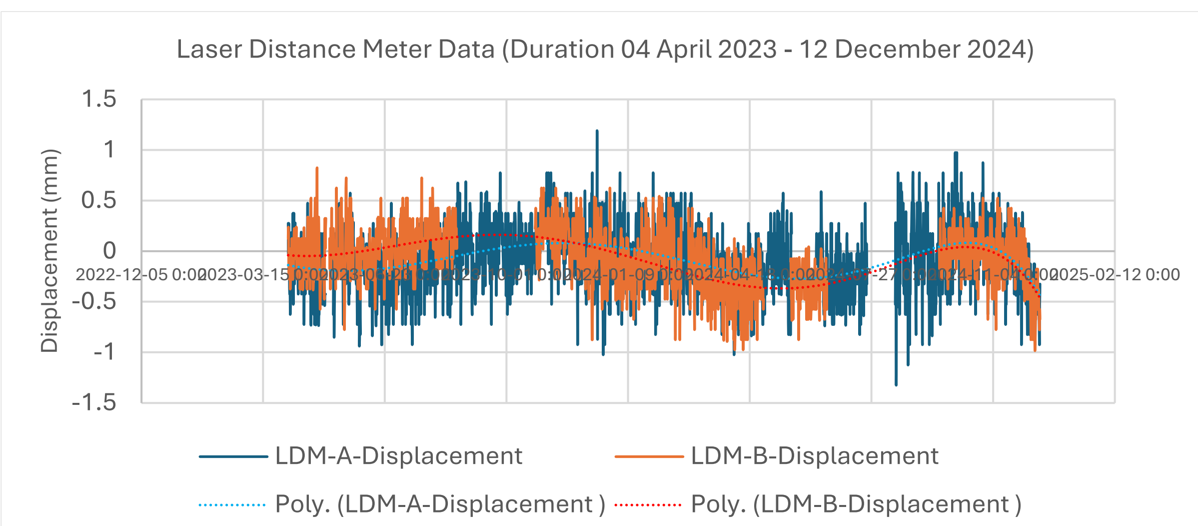


Figure 4: Laser Distance Meter data

Correlation between ambient temperature and Laser Distance Meter data is examined and presented in Figure 5.

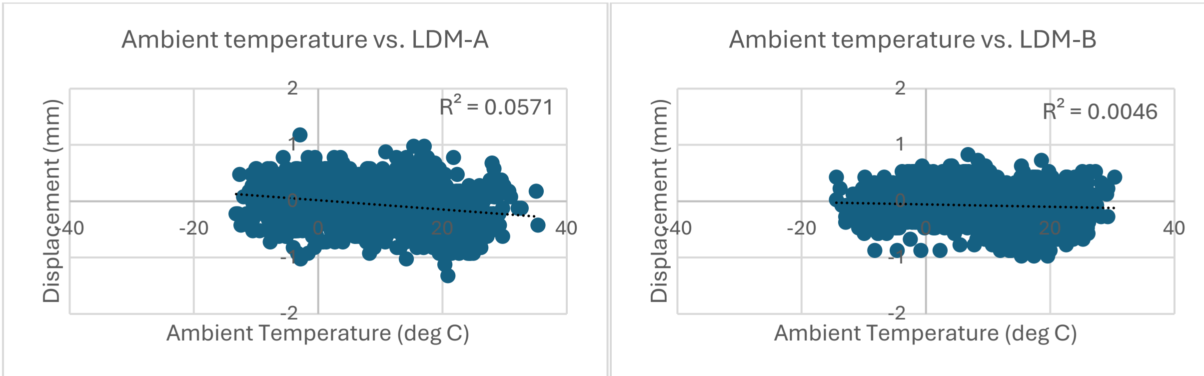


Figure 5: Ambient temperature vs. Laser Distance Meter data (R^2: Correlation coefficient)

Figure 5 shows a weak correlation between ambient temperature and Laser Distance Meter data, as the estimated correlation coefficient values (R^2) are significantly low. This highlights that there is almost no effect of ambient temperature on the Laser Distance Meter data.

Settlement Monitoring System

Settlement monitoring system is essential for tracking the settlement of masonry columns and walls during ongoing construction activities. In the CBR project, this system measures two key parameters: (a) differential settlement between columns/walls using Tilt Beams, and (b) relative settlement of columns /walls with respect to a stable benchmark using a Liquid Level system.

Tilt Beam

In the CBR project, Tilt Beam sensors are used to measure continuous differential settlement along their length. Tilt Beams utilize Micro-Electro-Mechanical Systems (MEMS) technology, which offers improved performance under varying ambient conditions. As part of the continuous monitoring system, differential settlement data is collected every six hours. Review Level and Alert Level notifications are sent when differential settlement records reach ±2 mm and ±3 mm respectively. Two Tilt Beams are installed to measure differential settlements between two pairs of masonry columns in the North-South direction. Data obtained from these sensors are shown in Figure 6.

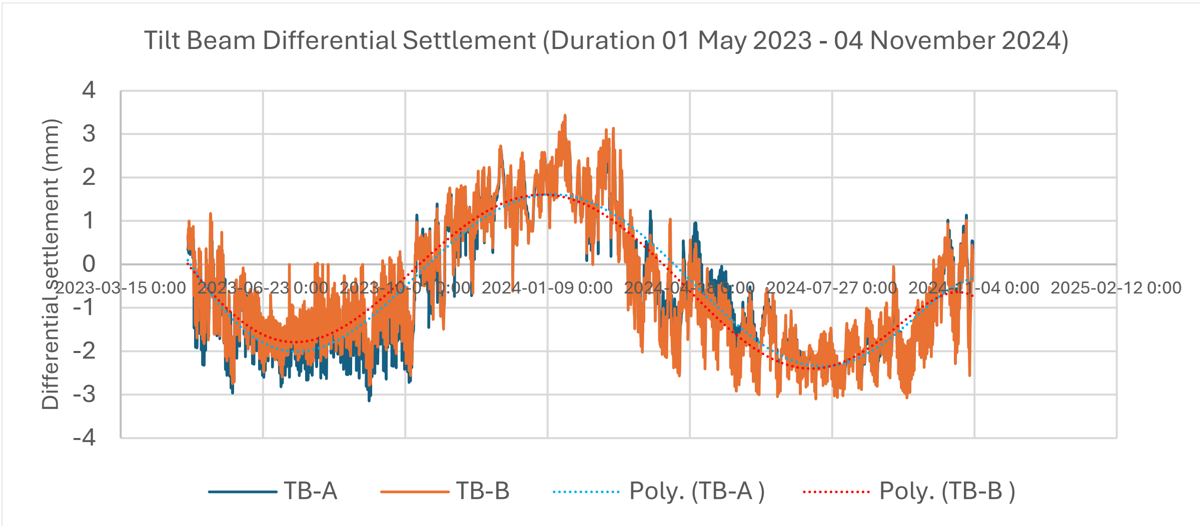


Figure 6: Tilt Beams differential settlement data

Correlation between ambient temperature and Tilt Beam differential settlement data is examined and presented in Figure 7.

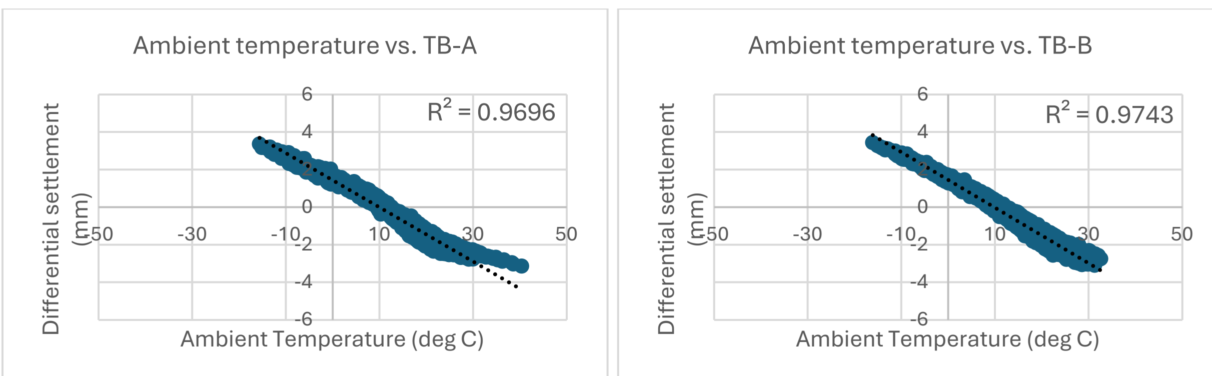


Figure 7: Ambient temperature vs. Tilt Beam differential settlement data (R^2: Correlation coefficient)

Figure 7 indicates a strong correlation between ambient temperature and tilt beam differential settlement data, with estimated correlation coefficient values (R^2) exceeding 0.90.

Liquid Level

The automatic liquid level system is designed for precise long-term monitoring of differential settlement in buildings, tunnels, and other civil structures. This system comprises a series of H-Level gauges hydraulically connected to a reference tank which is installed in a non settling environment. Each H-Level gauge features a high-resolution pressure sensor that measures the liquid head resulting from the elevation difference between the gauge and the reference tank. As part of the continuous monitoring system, differential settlement data is collected every hour. Review Level and Alert Level notifications are sent when differential settlement records reach ±2 mm and ±3 mm respectively. In the CBR project, four liquid level sensors are installed to monitor the settlement of four masonry columns. The data obtained from these sensors are shown in Figure 8.

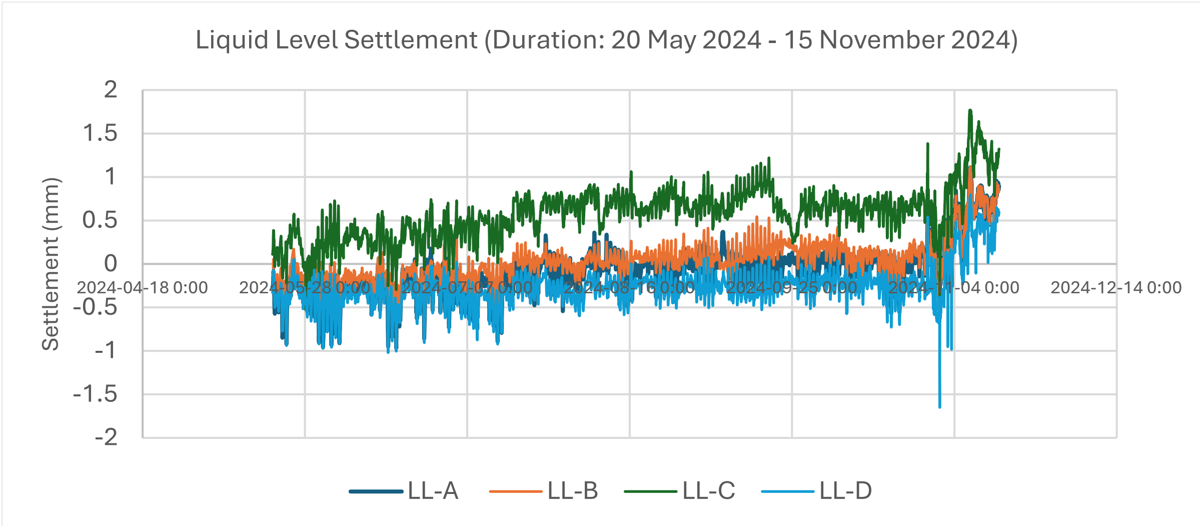


Figure 8: Liquid level settlement data

Correlation between ambient temperature and Liquid Level settlement data is examined and presented in Figure 9.

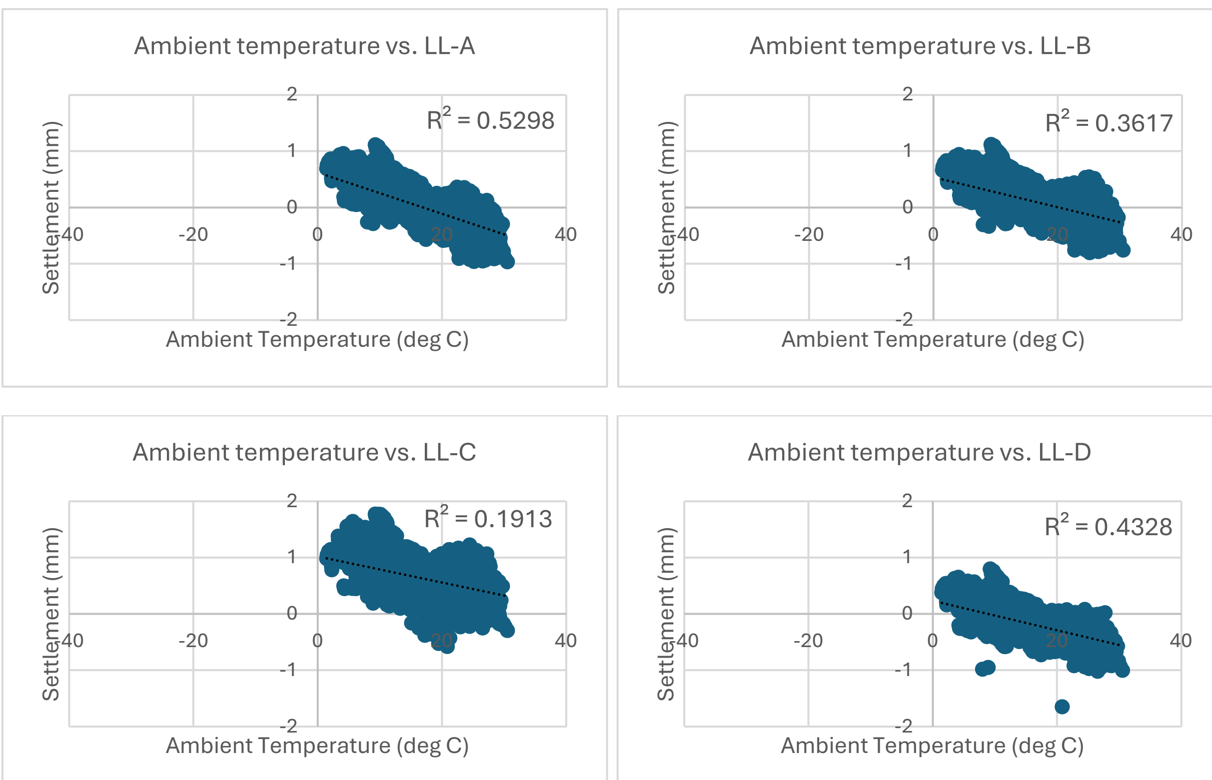


Figure 9: Ambient temperature vs. Liquid level settlement data (R^2: Correlation coefficient)

Figure 9 shows a moderate relationship between ambient temperature and liquid level settlement data, with correlation coefficient values (R^2) that are neither very high nor very low. This suggests that ambient temperature has a moderate effect on liquid level settlement data.

Tilt Monitoring System

The tilt monitoring system is important for tracking tilt of masonry columns/walls during ongoing construction. In the CBR project, this system measures the relative tilt between two points using Tilt Beams, which are equipped with MEMS sensors. These sensors measure tilt along the length of a beam. The system continuously monitors tilt data, recording it every six hours. It has a Review Level notification for tilt changes of ±0.10 degrees and an Alert Level notification for changes exceeding ±0.15 degrees. Data obtained from two of the Tilt Beams are presented in Figure 10.

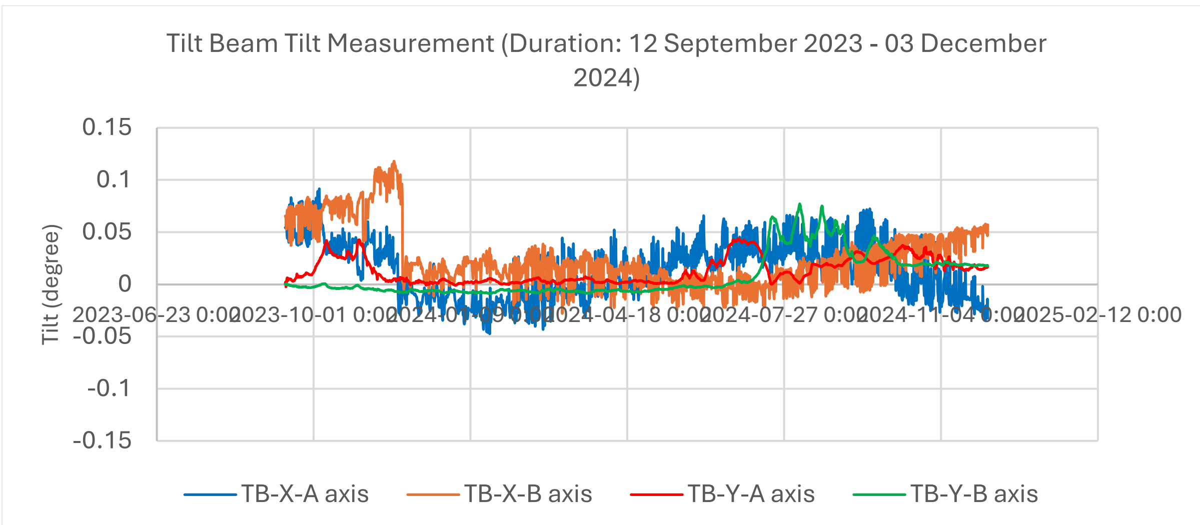
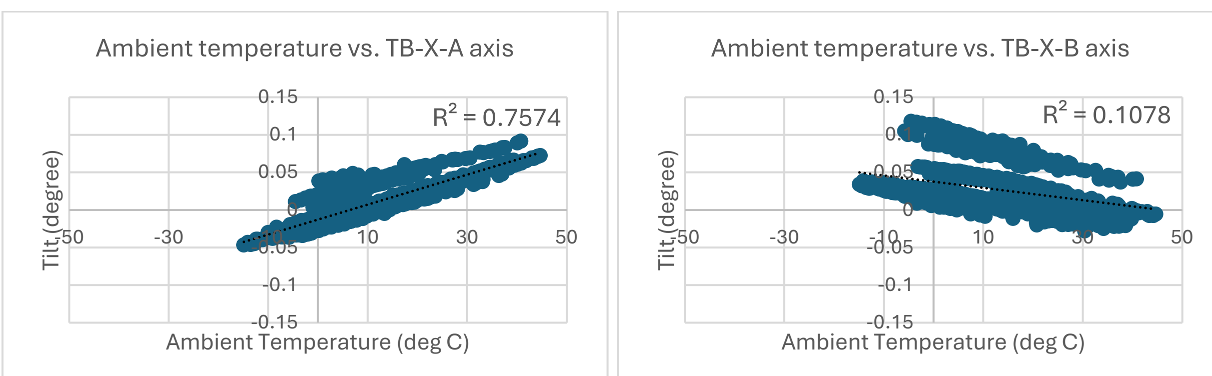


Figure 10: Tilt Beams tilt data

Correlation between ambient temperature and Tilt Beam data is examined and presented in Figure 11.



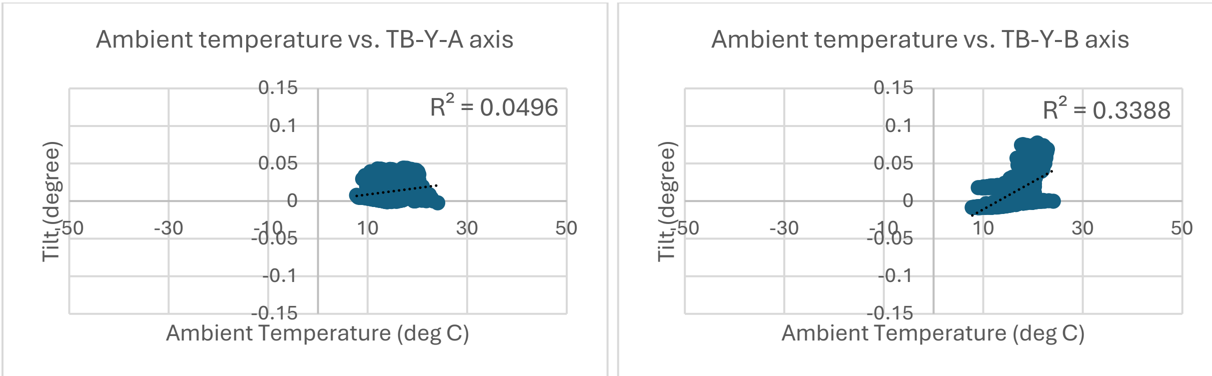


Figure 11: Ambient temperature vs. Tilt Beam data (R^2: Correlation coefficient)

Figure 11 shows a moderate correlation between ambient temperature and Tilt Beam-X-A axis data, with correlation coefficient values (R^2) that are neither very high nor very low. Figure 12 illustrates the construction-related tilt of masonry columns/walls after removing temperature effects from the raw tilt data. Maximum construction related tilt is observed in Tilt Beam-X-B axis amounting to approx. 0.14 degree and no significant damage was observed.

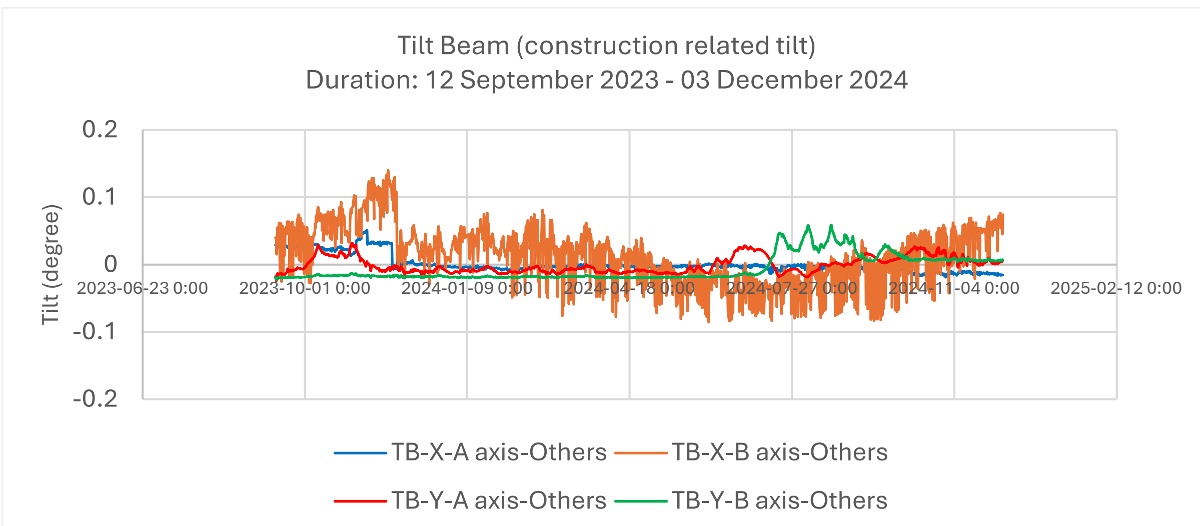


Figure 12: Construction related tilt

Vibration Monitoring System

Monitoring vibrations from nearby construction activities is crucial for preserving heritage masonry structures, especially those made of Tyndal stones. Due to their heritage value and material properties, it's essential to control and monitor vibrations propagating through these stones. In the CBR project, geophone-based sensors are used to measure vibrations within a frequency range of 2-250 Hz and a Peak Particle Velocity (PPV) of 254 mm/s. These sensors are crucial as they can detect both high and low frequency vibrations, that can cause structural damage depending on their PPV. Vibration monitoring system continuously monitors vibrations, sending notifications when they exceed project-defined threshold values. Review and alert limits are set based on a sliding scale relationship between PPV and Hz. Table 1 outlines the different Review and Alert Levels threshold values implemented in the CBR project.

Table 1: Review and alert level threshold values for vibration in CBR project

Dominant Frequency range (Hz)	Review Limit PPV (mm/s)	Alert limit PPV (mm/s)
<10	2	3
10 to 40	2 to 15	3 to 17.5
>40	15	17.5

Figure 13A illustrates events during a specific timeline reading from the device during an active construction day at the site. The red line in the diagram represents the Alert Level threshold, while the yellow line indicates the Review Level threshold.

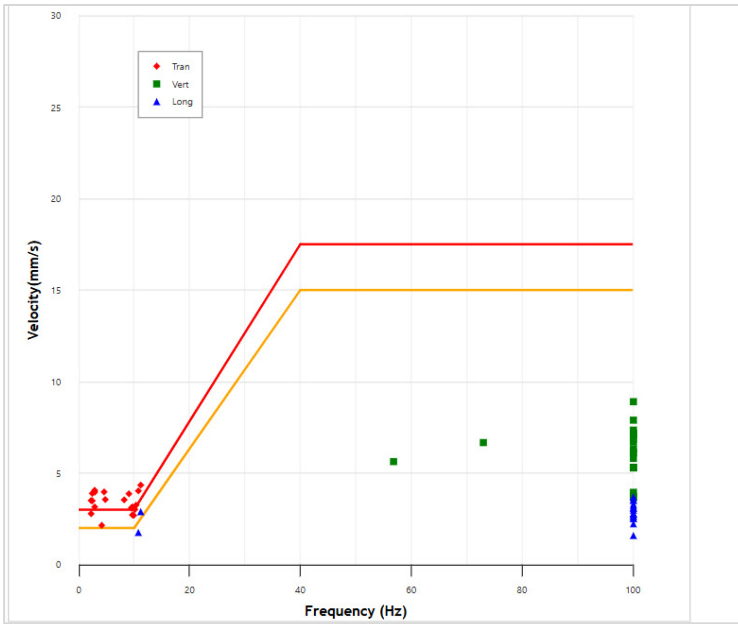


Figure 13A: Vibration data, and exceedance waveform; from left to right

Figure 13B illustrates an exceedance waveform for a typical vibration event.

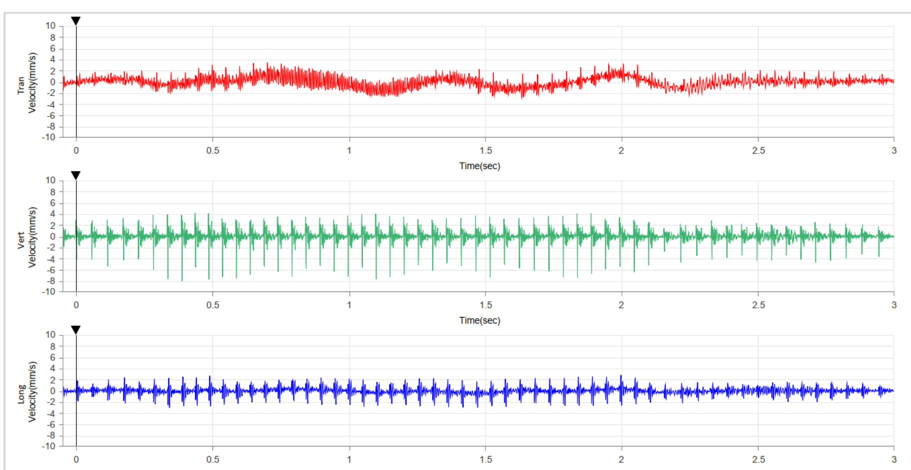


Figure 13B: Vibration data, and exceedance waveform; from left to right

The exceedance shown in Figure 13B occurs in the transverse direction and produces a waveform with a 3-second event duration. The waveform indicates that the sensor experiences continuous vibrations, which are likely to cause damage to the Tyndal stone. Due to the amount of low-frequency exceedances on the Tyndal stone, a visual inspection of the area was conducted to check for any damage.

CONCLUSION

BHMP data obtained in the CBR project indicates that some sensor datasets are strongly affected by ambient temperature, depending on the sensor's location (indoor or outdoor) and the type of measurement parameters. To accurately assess construction-related parametric values (displacement, settlement, tilt, vibration, etc.), changes due to ambient temperature shall be subtracted. Linear regression equations are used to calculate the effect of ambient temperature, assuming the effect of the ambient temperature on the measured parameter is linear. Displacement monitoring systems show seasonal trends in Joint Meter data, with joints moving proactively in winter. Frequent inspections are conducted to check for cracks, such as a recent crack in a stone archtop, which is now under constant monitoring. Laser Distance Meters show no significant seasonal changes in pier distances, with minor variability (±0.2 mm) attributed to construction vibrations in the adjacent area. Tilt Beam differential settlement devices exhibit more temperature-driven variability than Liquid Level monitoring devices. No differential settlement is observed in the Tilt Beams between the piers. An anomaly in LL-C data is traced to a sagging tube anchor, that was tightened after inspection. Tilt Beams measuring tilt in masonry walls captured tilt in the Tilt Beam-X in B axis. After receiving alerts, inspections found no damage, and additional shoring was provided to the wall, and anchoring was done for the underneath rock. Vibration monitoring during demolition works helped prevent damage to heritage Tyndal stones. Alerts prompt contractors to use different equipment and conduct damage inspections. The paper summarizes sensor types, their temperature dependencies, and threshold parametric values during construction and rehabilitation. Post-construction monitoring of the building, develop required strategy and attribute different parametric values to different sensors are works to be done in future.

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