

Satellite-based InSAR Monitoring –Validation on Victoria Bridge in Montreal, Canada

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ABSTRACT: Public transportation agencies need reliable monitoring technologies to provide advance warnings of pending failure of their valuable assets, probability of which may increase due to climate change. To address this concern, a partnership was formed to validate a satellite-based bridge monitoring approach by comparing its results to analytical predictions. A previous validation study on a new bridge made of concrete deck on steel box girders found a good match between satellite-measured thermal displacements and those from numerical predictions calibrated on sensor measurements. With the aim of validating the approach on different structural systems, this paper presents the findings of a 2nd validation study on a historical bridge made of steel grating deck supported by a metal truss structure. Two sets of satellite imagery with different viewing angles were used to allow decomposition of measurements into vertical and longitudinal components of displacement for direct comparison with predictions. Results confirmed the validity of the approach and indicated which bridge features can be best monitored accurately.

1 INTRODUCTION

Highway bridges are critical to national road transportation networks and are in urgent need of rehabilitation in many countries (e.g. Canada and the U.S.) owing to ageing, limited capital investment, and insufficient inspection and maintenance (Transport Canada 2012). Remote monitoring technologies can provide extremely useful data on the performance and reliability of bridges and climate change adaptation measures as bridge owners in North America have been struggling for decades with how to cost-effectively rehabilitate their portfolios of bridges (U.S. D.O.T. et al. 2007). By conducting interferometric synthetic aperture radar (InSAR) analysis on acquired radar satellite imagery, the movement at hundreds or even thousands of point targets on a single bridge structure and its nearby foundation can be monitored with sub-centimeter accuracy (Marinkovic *et al.* 2007). Such satellite-based monitoring can also be conducted at the network level to cost-effectively screen several bridges at once for stability issues and flag them for in-situ inspection (Acton 2013).

Using satellite imagery from Canada's RadarSat-2 satellite, a previous validation study on a new bridge made of continuous spans of a concrete deck on steel box girders found good match between satellite-measured thermal displacements and numerical predictions calibrated on sensor measurements (Cusson et al. 2018). With the aim of validating the approach on different structural systems, this paper presents the findings of a 2nd validation study on a historical bridge made of simple spans of a steel grating deck supported by a metal truss structure. In future phases of the project, it is proposed to develop a decision-support tool based on radar satellite data to assist bridge engineers in performance assessment and maintenance planning of highway bridges.



2 BRIDGE SITE AND ACQUIRED RADAR IMAGERY

The 160-year old Victoria Bridge – owned by Canadian National Railway (CN) – crosses the St. Lawrence River and links the cities of Montreal and Saint-Lambert in the province of Quebec, Canada (Fig. 1). The 3 km long bridge consists of through trusses, deck trusses and girder spans that carry two railway tracks and four narrow roadway lanes located over icebreaking masonry piers. The railway tracks are supported by a deck, which is made mostly of timber bridge ties, while the roadway riding surface is mostly steel grating. The roadway is carried on cantilevered floor beam extensions on through trusses, which is carried under the railway tracks on deck trusses.

More specifically, the bridge consists of 26 simply-supported spans (with specific support types shown later in Fig. 4) and has an overall deck width of 20.4 m. Starting from the Montreal shore, the span configuration is as follows: 12 regular through truss spans of 77.4 m (as illustrated below in Fig. 1a), followed by 1 longer through truss span of 106.1 m at the centre of the bridge, 3 regular through truss spans of 38.1 m, 4 short girder spans of 38.1 m on average (before the track diversion; see Fig. 1b), and 6 regular through truss spans of 77.4 m. Note that the track diversion portion of the bridge and 2 lift spans over the Saint-Lambert locks are not included in the analysis.



Figure 1. Typical spans of Victoria Bridge: (a) Side view from Saint-Lambert; (b) Elevation view

For typical InSAR analysis, scenes can be obtained from Radarsat-2 at a 24-day frequency for two satellite directions (ascending, when satellite navigates from south to north poles; and descending, from north to south poles), for different beam modes (with various resolutions and footprints), and for different viewing angles (20° to 50° from vertical). For monitoring the Victoria Bridge, Spotlight-A (SLA) beam mode was selected, which is best-suited for bridge monitoring applications since it has the capability to provide the best horizontal ground resolution (under 2.5 m) and smallest footprint ($18 \times 8 \text{ km}^2$). Two image stacks with opposite viewing geometries were selected. First one was the SLA26-asc stack in ascending direction; looking sideways to the East with a 48° incidence angle (Fig. 2). The second one was the SLA12-des stack with a descending direction; looking sideways to the West with a 39° incidence angle (Fig. 2). A total of 19 scenes were available for the analysis from the SLA-26-asc stack and 28 scenes from the SLA12-des stack, covering a two-year monitoring period from May 2016 to August 2018. It should be noted that only one stack is normally required to monitor a bridge on an operational basis; however, two independent stacks were analyzed in this study since one of the goals was to investigate the feasibility of performing 2D decomposition on the line-of-sight (LOS) displacement data from two independent stacks of satellite imagery.

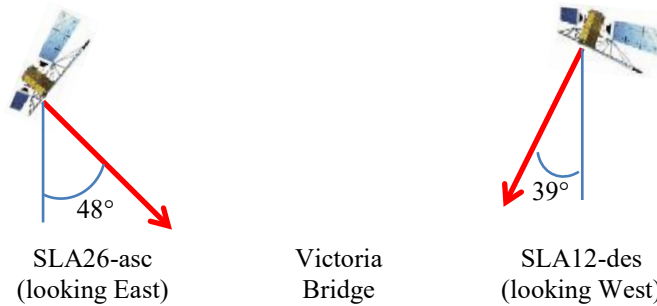


Figure 2. Viewing geometries selected for monitoring the Victoria Bridge.

3 INSAR ANALYSIS OF SATELLITE IMAGERY

This section briefly summarizes the interferometric analysis of SAR imagery conducted by Greene Gondi et al. (2019) to obtain displacement data for the bridge under consideration.

Synthetic Aperture Radar (SAR) is fundamentally an active ranging measurement technique that generates images by bouncing microwaves from Earth's surface. Each pixel in an interferogram comprises a phase difference (from 0° to 360°) between two distinct SAR snapshots of a given resolution cell. The interferogram phase is cumulatively sensitive to all geometric and physical variables that affect the return path of the microwaves between the satellite and Earth's surface. Hence, the phase is proportional to surface topography, surface displacement along satellite LOS, atmospheric pressure, and water vapour. Knowing the phase difference and the radar wave length (5.66 cm for Radarsat-2), the relative displacement of a given target over time can be estimated. The persistent scatterers interferometric synthetic aperture radar (PS-InSAR) method allows the detection of point-like coherent targets in the radar image that are dominated by a stable reflector called a persistent scatterer. This method was selected because it provides better discrimination between targets of high and low coherence (or quality) and is better at eliminating water targets.

The analysis of radar signal returns (or backscatters) from bridges can be complicated due to the combination of layover, shadow and multi-bounce effects. For instance, layover effects can occur when spatially separated scattering elements are at the same radar range and may thus appear to overlap in the radar image. For example, at the Victoria Bridge, the near-range portion of the steel truss is in layover with a portion of the near-range roadway, and a portion of the near-range roadway is in layover with unstable water surface, which may act to reduce coherence. Concurrently, shadow effects can occur when incident radar signals are blocked by other parts of the structure. For example, at the Victoria Bridge, a portion of the far-range roadway is in the shadow of the central truss over the railway. Furthermore, multi-bounce effects can occur when radar signals bounce off more than one physical object before returning to the satellite. At the Victoria Bridge, strong double-bounce returns were observed from the deck railings and the sides of the truss. More details on these effects can be found in Ferretti et al. (2007).

The PS-InSAR method, using a multi-model linear regression analysis, was used to extract the following key parameters from radar satellite imagery:

- Height (m) – fitted against perpendicular baseline (stereo sensitivity) data;
 - Displacement thermal sensitivity ($\text{mm}/^\circ\text{C}$) – fitted against ambient temperature data;
 - Displacement time rate (mm/year) – fitted against time from the first image acquisition;
 - Coherence (ranging 0 to 1) – confirming quality of fit and reliability of the processed data.
- In this case study, targets with a coherence of at least 0.8 were kept for the final analysis.

In a final step of the analysis, 2D decomposition of the LOS data acquired from the two stacks was performed to obtain the true vertical and longitudinal components of displacement. Figure 3 shows the height data as well as the displacement linear rate and the displacement thermal sensitivity estimated over the Victoria Bridge for the SLA26-asc stack. Similar results from the SLA12-des stack were also obtained but are not shown here due to space limitation. The height data reveal large height estimates along the entire bridge. An increase in height is observed from each access ramp onto the bridge. Variations of height can be observed along the bridge from span to span, which may be attributed to multiple elements of the bridge being illuminated by the radar (e.g. truss with height of 12 meters vs. railings at deck level).

The displacement linear rate data do not reveal any significant movement over the superstructure, deck, or any other areas near the bridge, including the approach slabs and the nearby roads. The displacement thermal sensitivity data show regular cycles of thermal movement along the bridge, with a change in polarity near the centre of the bridge. This last set of data (i.e. thermal sensitivity) is the set of measurements that will be compared to thermal displacement predictions in the next section of this publication.

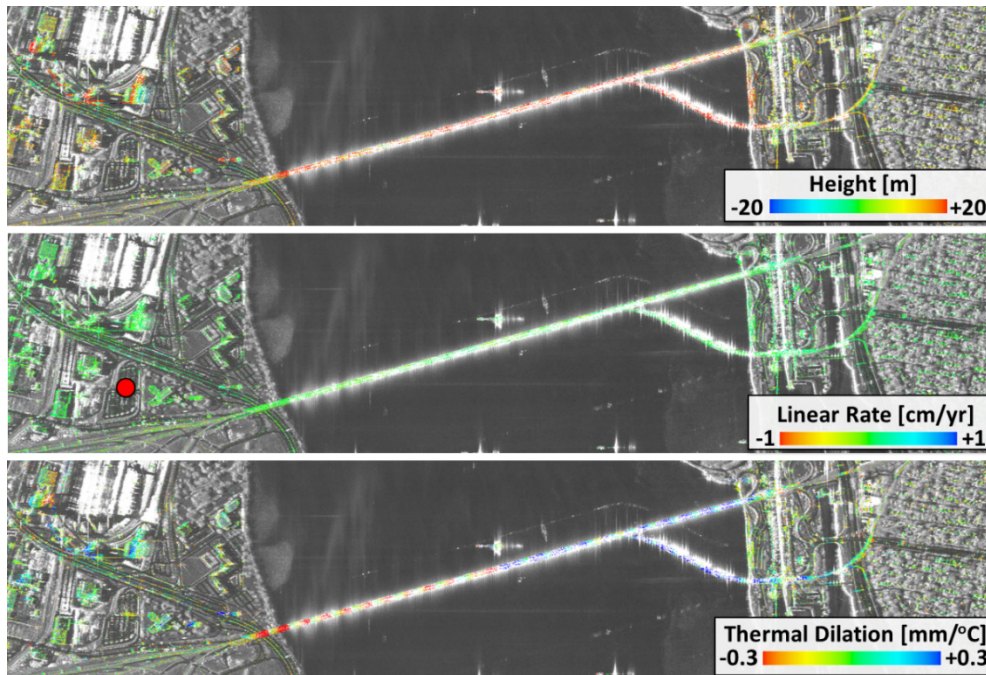


Figure 3. LOS height, linear rate and thermal sensitivity for SLA26-asc stack at Victoria Bridge from May 2016 to August 2018 (Greene Gondi *et al.* 2019).

4 BRIDGE THERMAL DISPLACEMENT PREDICTIONS

In a previous NRC study (Cusson *et al.* 2018), it was demonstrated that finite element model (FEM) predictions of a bridge thermal behaviour can be used directly to validate InSAR-derived thermal displacement results. For the Victoria Bridge case study, the same approach is used except that simple analytical calculations are made assuming linear static structural behaviour and isotropic linear materials.

The entire bridge is made of metal elements, for which an elastic modulus of 200 GPa and a thermal expansion coefficient (CTE) of $0.000012/^\circ\text{C}$ are assumed. The deck width is 20.4 m and the steel truss height above the roadway is 12 m, while 21 of the 26 spans have a length of 77.4 m. The supports at each simply-supported span are a roller at one end at the pin at the other end.

In the vertical direction, a bridge made of the same material in the deck and superstructure will exhibit very small displacement at deck level due to changes in temperature assuming small thermal gradient across the section depth (Eq. 1). However, vertical elements of the bridge are assumed to expand or contract in the axial direction due to temperature variations (Eq. 2).

In the longitudinal direction, the bridge will display thermal movement proportional to the length of the bridge span under consideration and the change in ambient temperature (ΔT), assuming that the bridge temperature is in equilibrium with the ambient temperature (Eq. 3). Based on the above assumptions, the vertical and longitudinal components of thermal displacement at the Victoria Bridge can be obtained as follows:

$$D_{th,Vb} = 0 \text{ (i.e. bending contribution due to CTE difference between materials)} \quad (1)$$

$$D_{th,Va} = L_V \times CTE \times \Delta T \text{ (i.e. axial contribution due to thermal expansion)} \quad (2)$$

$$D_{th,L} = L_L \times CTE \times \Delta T \text{ (i.e. axial contribution due to thermal expansion)} \quad (3)$$

where $D_{th,V}$ = thermal displacement in the vertical direction; $D_{th,L}$ = thermal displacement in the longitudinal direction; L_V = length of vertical element; L_L = length of longitudinal element.

Since the goal is to compare analytical calculations (typically expressed along the vertical and horizontal directions) with InSAR measurements from the inclined-looking satellite (typically expressed along the LOS direction), one needs to convert one system of measurements to the other. In such case, the satellite-bridge viewing geometry needs to be considered and requires the knowledge of the following parameters:

α : Incidence angle of the satellite line-of-sight (48° for SLA26 and 39° for SLA12)

β : Angle between satellite track heading and bridge azimuth (73° for SLA26 and 234° for SLA12)

With the above two parameters, Equation 4 can be used to calculate the LOS displacement from the calculated vertical and horizontal components of displacement, as follows:

$$\Delta LOS = -\Delta V \cos \alpha - \Delta L \sin \alpha \sin \beta \quad (4)$$

where ΔLOS is line-of-sight displacement (or range); ΔV is vertical component of displacement; ΔL is longitudinal component of displacement; and the angles are defined above. As far as the horizontal displacement is concerned, Eq. 4 indicates that InSAR measurements from Radarsat-2 will be most sensitive to the longitudinal component for East-West oriented bridges ($\beta = 90^\circ$ or 270°) and to the transverse component for North-South oriented bridges ($\beta = 0^\circ$ or 180°).

5 ASSESSMENT OF SATELLITE-BASED MONITORING APPROACH

As it was found in previous NRC study by Cusson *et al.* 2018, one particular set of InSAR data obtained from the Radarsat-2 satellite can be directly compared to thermal displacement predictions, which was the displacement thermal sensitivity expressed in units of displacement per temperature, and is typically plotted as a function of the position along the longitudinal axis of the bridge. The displacement thermal sensitivity represents the bridge displacement (vertical or horizontal) resulting from a global temperature increase of 1°C . This comparative approach between InSAR measurements and analytical predictions of thermal sensitivity is used here to explain and validate the InSAR data sets measured by Radarsat-2 over the monitored bridge.

A first comparison is made by looking at the longitudinal component of thermal sensitivity along the bridge layout line. The InSAR data set was calculated from corresponding point targets of the SLA26-asc and SLA12-des image stacks. A total of 4,978 valid points were available for the comparison to the analytical prediction, as shown in Fig. 4. An excellent match in terms of extent and slope is found over the entire length of the bridge. It is nice to observe the well-captured effects on longitudinal thermal sensitivity from (i) span length (three lengths: 38.1 m, 77.4 m and 106.1 m) and (ii) movement direction according to the support conditions (see Fig. 4 where F=Fixed and E=Expansion). Data over Span 11 (between 790 m and 868 m) seem to indicate lower values of longitudinal thermal sensitivity compared to either the prediction or the InSAR measurements over identical adjacent spans.

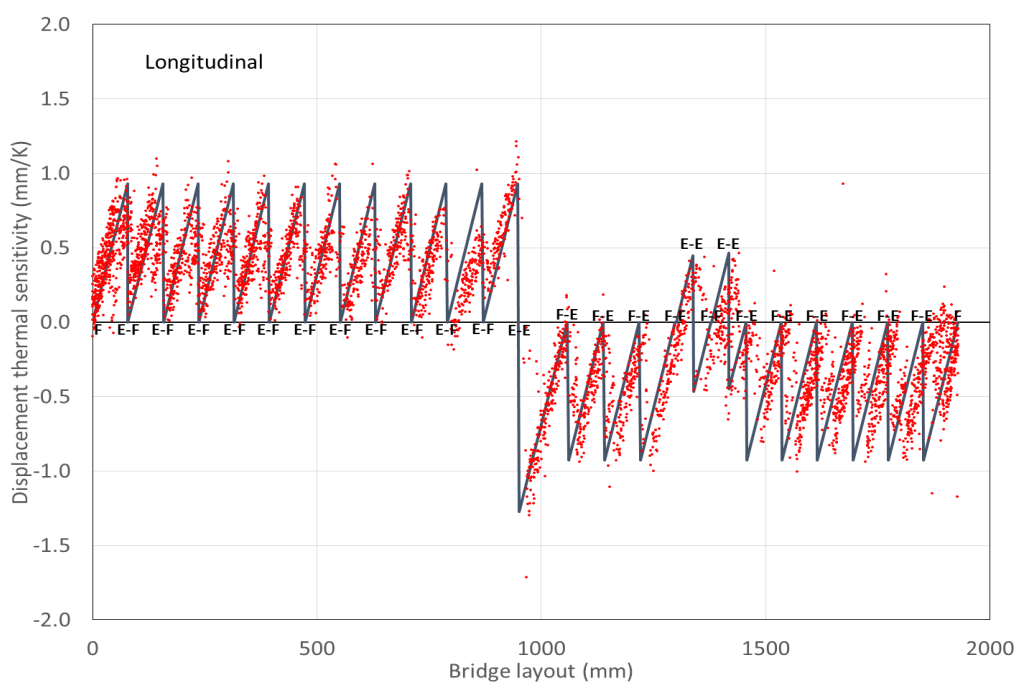


Figure 4. Comparison between InSAR and predicted thermal sensitivity data for the longitudinal direction decomposed from the SLA26-asc and SLA12-des stacks (Victoria Bridge; May 2016–August 2018).

A second comparison is made by looking at the LOS measurement points taken directly from each stack of satellite imagery. InSAR data with high coherence above 0.8 were selected, resulting in 16,703 points for SLA26-asc stack (Fig. 5) and 32,493 points for SLA12-des stack (Fig. 6). The LOS predictions were calculated for the respective satellite viewing geometry, where the blue and green lines represent the predictions at the deck level and top chord of truss, respectively.

Apart from the very good match, the predominant importance of the longitudinal component of displacement thermal sensitivity is clearly seen. As observed above in Figure 4, the trend at Span 11 with the slightly lower values of thermal sensitivity is observed again in Figure 5; however, the trend is not seen in Figure 6 from the SLA12-des stack. Another observation concerns the second half of the bridge (i.e. spans 13 and up), which appears to have higher measured values than expected for each concerned span.

These two observations seem to indicate that it is an issue related to the stack viewing geometry, rather than an issue with the thermal behaviour of the bridge. Viewing measured data from each satellite stack may give additional perspective on the interpretation of movement detected by each satellite stack since the north side of the bridge was predominantly seen by the SLA26-asc stack and the south side of the bridge was predominantly seen by the SLA12-des stack.

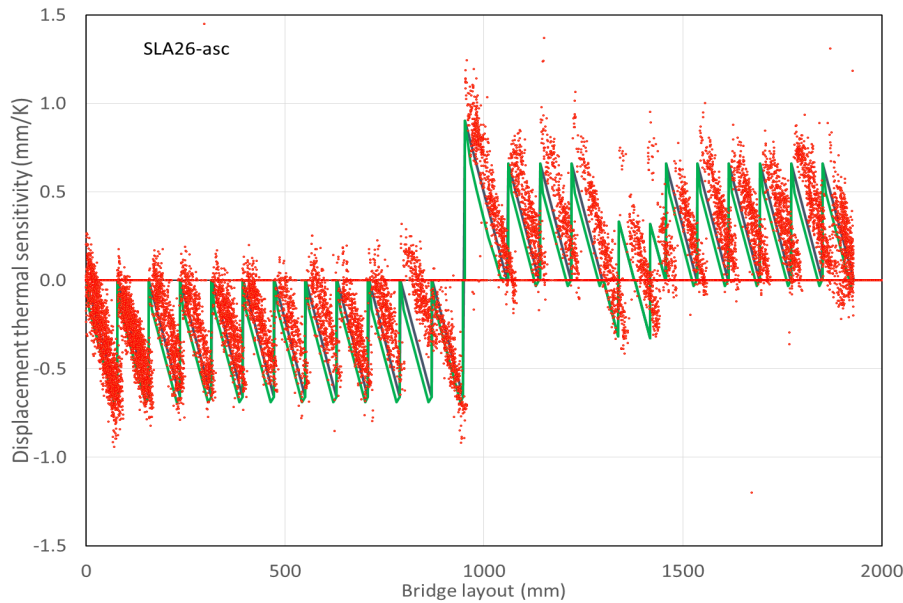


Figure 5. Comparison between InSAR and predicted thermal sensitivity data for the LOS direction obtained from the SLA26-asc stack (Victoria Bridge; May 2016–August 2018).

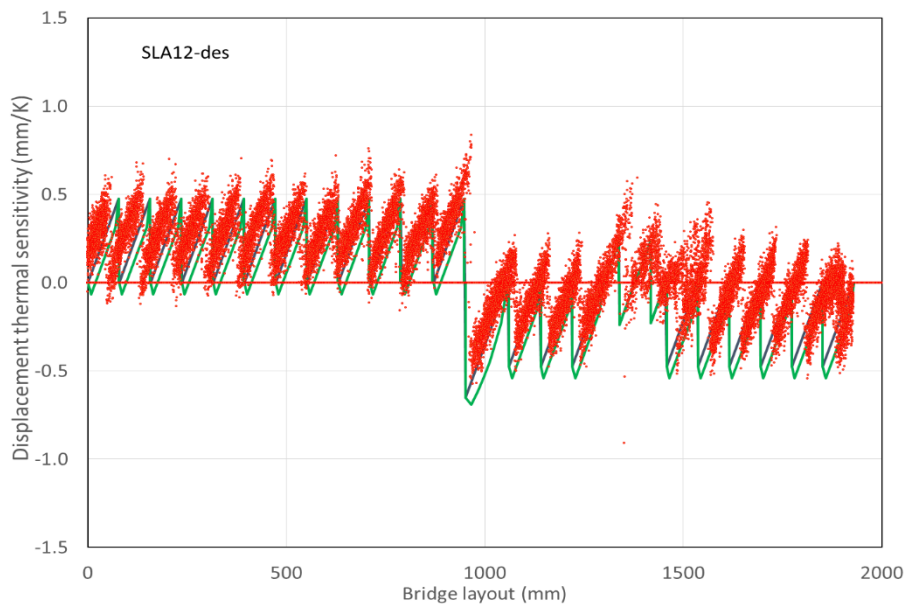


Figure 6. Comparison between InSAR and predicted thermal sensitivity data for the LOS direction obtained from the SLA12-des stack (Victoria Bridge; May 2016–September 2018).

6 CONCLUSIONS

Two independent stacks of satellite imagery from Radarsat-2 were collected over the Victoria Bridge for a period of two years and then processed and analyzed with the InSAR method to extract the bridge displacement measurements. The validation consisted of comparing the InSAR displacement measurements to analytical predictions of thermal displacement for each stack of satellite imagery.

The comparisons showed good agreement, in general, between the thermal displacement measurements and their analytical predictions both based on available ambient temperature data for the bridge location. It was therefore possible to explain most of the trends observed in the satellite measurements, which, for example, depended on factors such as span length, support conditions, superstructure height, and thermal expansion of the main structural materials. A few outlier groups of InSAR data points, however, could not be explained readily, which may be due to InSAR processing difficulties related to 3D geo-localization, layover effects, and other factors, especially when it is difficult to know from exactly which element of the bridge a given signal is originating. It was found useful to have two stacks of satellite imagery to confirm a given observation with a second independent image stack looking at the bridge from a different angle. Another benefit from having InSAR data from two opposite stacks is the possibility to perform a 2D decomposition on the combined data sets in order to obtain the true vertical and true horizontal (longitudinal or transverse) components of displacement, which can help identify the source of movement. However, these benefits come at more than twice the computational cost. A second type of displacement data available from the satellite imagery was the displacement linear rate (mm/year), which does not depend on temperature, and thus can be the result of mechanical effects, soil settlement, etc. For the Victoria Bridge, the displacement linear rate data coming from the two stacks of satellite imagery indicated very little movement. In summary, the results so far show great promise and value in applying satellite-based technology for the remote monitoring of highway and railway bridges in order to optimize preventive maintenance management, extend structural lifespan, minimize traffic disruptions due to late repairs, and ensure structural integrity after extreme climatic events.

7 ACKNOWLEDGMENTS

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