Bridge Remote Sensing Using TerraSAR-X Satellite

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ABSTRACT: Routine safety inspections performed at two post-tensioned bridges located in the southeastern US state of Virginia revealed extensive cracking in the concrete girders. Subsequent tests indicated widespread problems traced to the inadequate quality of tendon grouting, resulting in a partially bonded condition. Interferometric Synthetic Aperture Radar (InSAR) technology was applied to monitor bridge displacements over time. The TerraSAR-X radar satellite, orbiting at 515 km above the Earth, acquired data at 11-day intervals over a period of 16 months. The data were processed with the SqueeSAR algorithm, resulting in the millimeter range precision of time-displacement series. SqueeSAR analyses performed on the TerraSAR-X Staring Spotlight data provided an exceptionally high density of measurement points within the area of interest, including very comprehensive coverage of both bridges. There were 1,228,464 distinct points with associated time series of displacements identified from the ascending geometry and 1,025,768 points obtained from the descending orbit. The resulting point density per square kilometer was 164,233 and 137,134 for the ascending and descending tracks, respectively. The results indicate that implementing a viable bridge performance monitoring program through the use of satellite remote sensing is feasible.

1 INTRODUCTION

The concept of long-term bridge displacement monitoring to detect precursors of permanent deformation is well established. Burdet (2010) studied the long-term deflections of several bridges in Switzerland over a 20-year period. Correlations established between ambient air temperature and bridge deformation were used to assess the severity of permanent deformations. Bažant et al. (2011) studied excessive creep deflections at numerous segmental bridges following the 1996 collapse of the KB Bridge in Palau, and determined that excessive long-term deflections of large-span prestressed segmental box girders are far more prevalent than previously though.

This study points to the applicability of the high resolution Synthetic Aperture Radar (SAR) data, acquired by an Earth-orbiting satellite, to sense bridge deformations remotely at periodic time intervals without the need to install any equipment on a bridge. Satellite-based interferometric techniques have already proven useful for detecting minute displacements of the Earth's surface over a wide range of applications (Ferretti 2014).

2 AREA OF INTEREST

The study focused on two concrete bridges linking the town of West Point, Virginia, with neighboring counties, as shown in Figure 1. The Eltham Bridge over the Pamunkey River, completed in 2007, is 1,629 m long with 49 spans. The Lord Delaware Bridge over the Mattaponi River, built in 2006, is 1,080 m long, with 28 spans. Both bridges are 20.7 m wide (face to face of curbs) and include two post-tensioned spliced girder units comprised of four spans with approximate lengths of 61, 73, 73, and 61 m, with bonded internal tendons. Lightweight concrete was used to cast spans longer than 36 m, including all post-tensioned spans. The York River, formed by the confluence of the Pamunkey and Mattaponi rivers merging at West Point, flows approximately 60 km east into the Chesapeake Bay.

Figure 1. Aerial view of the West Point bridges.

Traffic volume estimates for 2017, compiled by the Virginia Department of Transportation (VDOT), indicate an annual average daily traffic (AADT) of 19,000 vehicles with 9% trucks and an AADT of 17,000 with 7% trucks for the Eltham and Lord Delaware bridges, respectively. Both bridges provide key transportation corridor serving many commercial interests and local communities.

3 PROBLEM STATEMENT

Structural problems with the West Point bridges were discovered purely by accident. Routine safety inspections conducted in the spring of 2015, following a period of prolonged sub-freezing temperatures, revealed extensive cracking and spalling at the webs of post-tensioned concrete girders at both bridges. The most likely cause was the freezing and the subsequent expansion of bleed water trapped in the internal post-tensioning ducts. Subsequent non-destructive tests and field drilling of test holes into some post-tensioning steel ducts revealed widespread problems traced to the inadequate quality of tendon grouting, as evidenced by the presence of voids, soft grout, and free water, resulting in a partially bonded condition (Sprinkel and Balakumaran 2017). Elevated levels of iron and sulfate were detected in the free water.

Potential tendon corrosion stemming from inadequate grouting is the primary forward concern. There are three post-tensioning tendons running inside each girder. Each internal tendon contains 12 strands with seven wires per strand. With seven girders supporting each of the post-tensioned segments, there are approximately 22 km of steel tendons installed in the West Point bridges. The problem is further compounded by the lack of adequate access to some tendon sections. Neither bridge is classified as being in poor condition as of 2018, but safety inspections are being performed more frequently.

4 PURPOSE AND SCOPE

VDOT is currently exploring various options for effective performance monitoring of the West Point bridges. This study was designed to assess the feasibility of using a remote sensing technique to monitor bridge displacements over time and provide early warning of excessive permanent deformations. The main focus was the ability to monitor bridge displacements along the entire structure with adequate precision and sufficient spatial resolution. This is usually a challenging task for long bridges where the extent of suspected damage has not been clearly delineated.

In the case of the West Point bridge monitoring, the measurement of surface deformations was used as a surrogate for evaluating corrosion-induced structural damage. It was recognized that the potential impact of impending tendon corrosion was not likely to manifest itself in terms of permanent structure deformations during the 1.3 years study period, considering that the bridges have been in service for only 10 years. The scope of the study was limited to evaluating the practicality of applying the remote sensing method to detect bridge displacement, although the researchers kept in mind the potential transferability of the measurement technique to a wide range of infrastructure monitoring needs.

5 METHODOLOGY

SAR is a remote sensing method that allows high resolution ground surveillance by combining (synthesizing) the return echoes of radar pulses emitted from a rapidly moving platform (Rosen et al. 2000). Radar signals are emitted and echoes are received hundreds of times per second, resulting in the amplitude image of the target surface. Typically, SAR is implemented by using airborne or satellite-based moving sensors. The main advantage of using active microwave frequency signals is that they are not obstructed by the cloud cover and ambient lighting. SAR systems can be effectively used under virtually all lighting and weather conditions. These characteristics make them particularly suitable for satellite-based platforms, resulting in a consistent and predictable acquisition schedule.

Although the SAR technology has been around since the 1950s (invented in the US by Carl Wiley of Goodyear Aircraft Corporation), recently there has been an explosive growth in the signal processing research regarding differential interferometry and displacement detection, focusing on the phase component of the return signal. In the early 2000s, the Polytechnic University of Milan advanced the concept of the permanent scatterer (PS) technique (Ferretti et al. 2001). This technique is based on the idea of analyzing a relatively long sequence of consecutive SAR images (at least 15 frames) to identify potential targets that do not change their electromagnetic signature throughout the entire dataset. By analyzing a stack of PS points, it is possible to quantify their time series of displacements. The essence of interferometric SAR (InSAR) centers on the phase shift measurement and analysis, resulting in mm-range precision in the differential displacement estimate of distinct scatterers (same PS points over the entire data stack). It is a relative measurement technique. Displacements associated with each PS point are always related to some stable reference point contained within the area of interest and within the time frame of observations. The initial radar acquisition forms a baseline for subsequent measurements. The use of a satellite platform allows the application of this technology over practically any point on the Earth's surface.

There have been several exploratory attempts to utilize satellite-based InSAR technology for bridge performance monitoring using C-band and X-band radar. Although the operational limitations have yet to be established, the interim results appear promising. Cusson et al. (2017) demonstrated the applicability of spaceborne monitoring to a major highway bridge in Canada where displacement data were found to compare favorably with the numerical modeling of ambient thermal data. Lazecky et al. (2017) provided case studies of using TerraSAR-X images acquired in the stripmap mode to monitor deformations at several bridges in the Czech Republic. The need for accurate thermal expansion modeling was identified as a significant obstacle needed to be resolved before implementation. Zhao et al. (2017) applied InSAR technology to monitor deformations at the Lupu Bridge in Shanghai. Linear deformation rates detected at key points along the steel arch structure were correlated with thermally induced seasonal displacements. Historical radar data, providing a look back in time, were used to predict bridge failure due to the scour of pier foundations (Selvakumaran et al. 2018; Sousa and Bastos 2013). InSAR results identified progressive bridge settlement in the vicinity of a pier prior to the time of collapse. Huang et al. (2018) outlined a methodology for bridge displacement monitoring in structural health evaluation. The sensitivity to anomalous displacements in the proposed health evaluation approach was estimated at approximately 1 cm.

Currently there are several commercially available radar satellites, suitable for routine InSAR monitoring. For the purposes of this study the researchers selected the TerraSAR-X radar imaging satellite to collect remote sensing data (DLR 2014; Scheuchl et al. 2009). This satellite is managed by DLR. It operates in low Earth orbit (LEO) at an altitude of 514 km, using X-band SAR (9.6 GHz). As the satellite circles the Earth in near polar orbit at a velocity of 7.6 km/s, it can acquire radar data in the so-called ascending or descending track, referring to its relative motion toward or away from the North Pole. The orbit is sun-synchronous, resulting in the satellite crossing each latitude at the same local time.

The SAR sensor look angle is oblique and perpendicular (range direction) to the flight path (azimuth direction). All acquisitions are performed along the line of sight (LOS). In this study, TerraSAR-X was passing over western Virginia while collecting the West Point image on the ascending track. It was passing over the Atlantic Ocean off the coast of Virginia on the descending track. The researchers selected acquisitions from the LOS off-nadir view angles of 34.91° and 37.04° for the ascending and descending tracks, respectively. Each data acquisition took approximately 1 second. Data were subsequently downlinked to the receiving stations in the Antarctic and northern Canada and then transferred to DLR offices in Germany. In contrast with some previous InSAR studies of civil infrastructure, the researchers selected the Staring Spotlight imaging mode of TerraSAR-X to achieve the maximum available resolution over a relatively small area of interest. This sophisticated acquisition mode makes it possible to collect radar data with up to 0.25 m spatial resolution (Airbus Defense and Space 2014). The size of each unprocessed image, containing amplitude and phase information, is approximately 400 MB in the Single Look Complex (SLC) binary format.

Data collection over the West Point bridges started in October 2016 and ended in February 2018. Trial acquisitions were performed initially to determine the visibility of the area of interest. Distinct thermally induced motion of bridge spans was observed from the interferogram generated from just a pair of successive radar images. Both ascending and descending images were collected. The time offset between ascending and descending orbits was 4 days, and each ascending and descending data frame was acquired every 11 days.

Simultaneous with the satellite remote sensing, the weather station data, including ambient air temperature, solar radiation, rainfall, and wind speed, were compiled on Eltham Bridge at 1-hour intervals using electronic dataloggers. Except for the weather station, there was no need to install any additional devices or field sensors at either bridge.

In this study there was no practical capability to capture and characterize traffic-induced live loads at the time of the satellite overpass. These loadings and the resulting bridge displacements may be considered random for the purposes of data analysis.

6 RESULTS

There were 37 and 38 images collected from the ascending and descending tracks, respectively. Radar data obtained from the TerraSAR-X satellite were processed by TRE Altamira using the SqueeSAR™ algorithm (Ferretti et al. 2011). Figure 2 shows the distribution of resulting PS points as determined separately from the ascending and descending geometries and co-registered on the topographic basemap consisting of high-resolution aerial orthoimage (TIF file) provided by VDOT. All results are available in the ESRI shapefile format and through an online webGIS portal developed for this study.

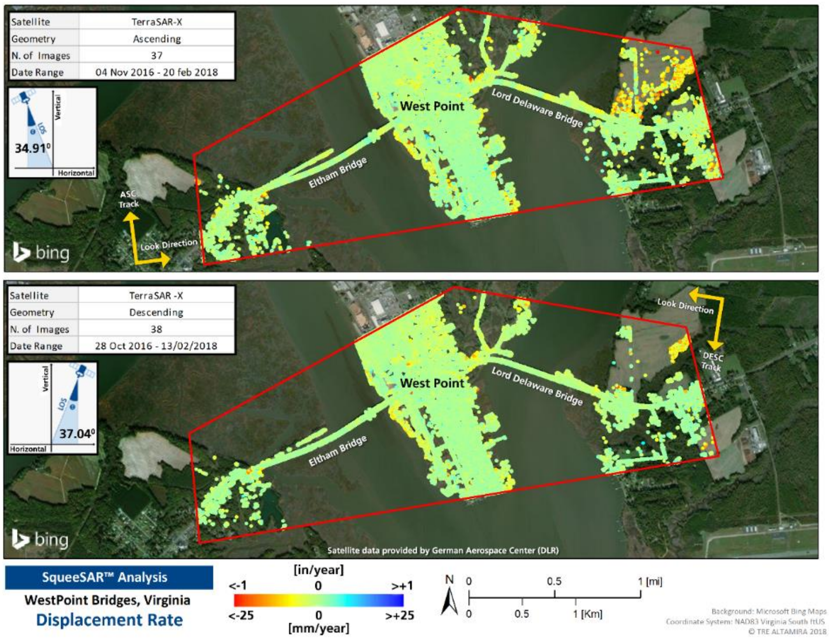

Figure 2. Distribution of ascending and descending PS points in the area of interest.

The SqueeSAR analyses performed with TerraSAR-X Staring Spotlight data provided an exceptionally high density of measurement points within the area of interest, including very comprehensive coverage of both bridges. In this respect, the results contrast markedly with some previous studies using C-band SAR and Stripmap mode of acquisition. There were 1,228,464 distinct points with associated time series of displacements identified from the ascending geometry and 1,025,768 points obtained from the descending one. The resulting point density per square kilometer was 164,233 and 137,134 for the ascending and descending tracks, respectively. The reference benchmark for all the displacement time series, chosen for its strong radiometric signal, was determined to be the top of a building located at the corner of Main Street and 16th Street in West Point.

In addition to displaying the PS point distribution within the area of interest, Figure 2 shows the color-coded linear displacement rates (typically referred to as velocities) of all individual PS points over the entire monitoring period. These LOS displacement rates are depicted according to the color scale representing the slope of the best fit line through the displacement time series. Movements away from the satellite are displayed in red shades. Movements toward the satellite are shown in blue shades. Green shades represent an essentially horizontal slope in the linear regression of the time series data. This type of display of individual scatterers allows for the rapid identification and delineation of local "hot spots" of excessive or outlier deformation, prompting the bridge owner to conduct a detailed follow-up inspection. The results shown in Figure 2 indicate no evidence of permanent deformations occurring at the West Point bridges, and specifically at the post-tensioned segments, during the period of study.

Since most of the observed bridge displacements are expected to be thermally induced (primarily in the longitudinal direction), it is informative to analyze the structure during the period of a strong thermal bias. Figure 3 shows color-coded deformation rates at the post-tensioned segment on Eltham Bridge for the June 2017 through January 2018 time period, corresponding to approximately 37°C ambient air temperature differential, with all displacements referenced to June 12, 2017. Representative surface profiles of LOS displacements along the outside girder, and extending beyond both expansion joints, are shown in the upper left. Each curve represents an oblique displacement profile on a particular date, with the horizontal axis being the reference for the June 2017 acquisition. The displacement time series of representative PS points at each end of the span are also shown in the lower right of Figure 3. These results are indicative of the net thermal contraction of the post-tensioning segment during the summer-winter period, as the western end moves away from the satellite (red shades) and the eastern end contracts toward it (blue shades). The oblique displacements of PS points were obtained from the ascending data, with the satellite passing over southwest Virginia, near the town of Blacksburg, at the time of each acquisition.

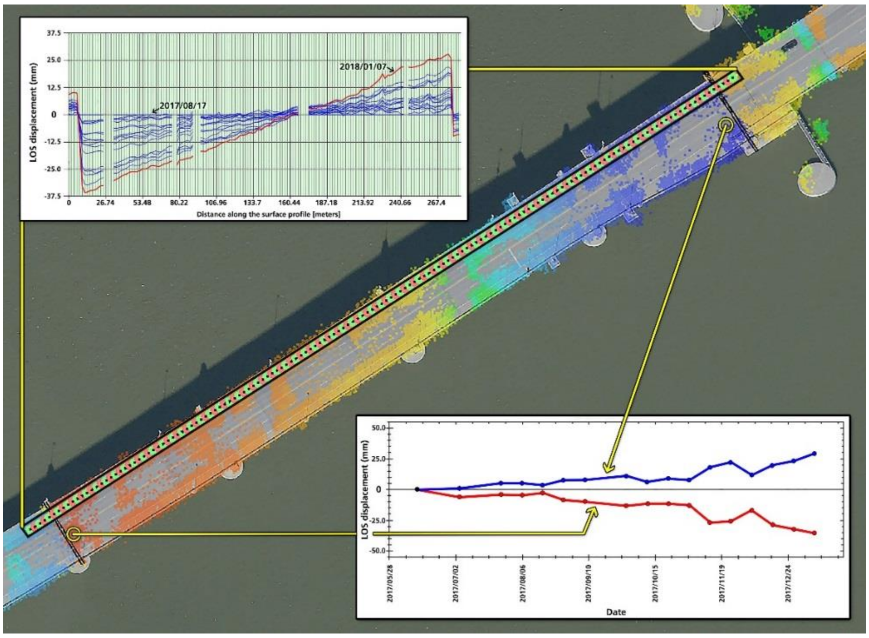

Figure 3. Ascending orbit LOS displacements at the Eltham Bridge post-tensioned segment.

Several data processing steps were required to isolate measurement points corresponding to the bridge deck surface. These steps included geospatial alignment using high resolution orthophotos and LiDAR elevation data. Figure 3 shows that the resulting individual PS points are distributed irregularly on the bridge deck surface, but their spatial coverage and density are sufficient to evaluate global displacement behavior of the structure. There are 13,784 distinct measurement points, with individual time-displacement histories, identified in Figure 3.

Overall, no permanent deformations were detected at the West Point bridges over the period of analysis. Seasonal bridge LOS deflections were approximately 24.0 mm and 22.0 mm at Eltham and Lord Delaware bridges, respectively. InSAR results generated by TRE Altamira with the SqueeSAR algorithm were provided with the nominal precision of ±5.0 mm for any single individual measurement and the annual deformation rate precision of ±1.0 mm/year.

7 DISCUSSION

The availability of millimeter-scale remote sensing of deformation offers potential new implementation opportunities in transportation infrastructure monitoring. What makes the satellite-based InSAR technology particularly attractive for long-term monitoring is that the accuracy of results increases over time with the number of acquisitions, as random atmospheric errors progressively cancel out. Acquiring radar data in the Staring Spotlight mode can provide a remarkably high density of measurement points on the superstructure.

In order to be of practical application to bridge owners, the presentation of InSAR results demands advanced data visualization techniques, including heavy reliance on the Geographical Information System (GIS) representation. Additional research is needed in this area to advance the current practice, with the successful implementation requiring a coordinated multidisciplinary team effort. The ultimate objective is to develop a decision support system that translates the complexities of satellite-based InSAR data processing into a process control tool that can be effectively managed by bridge engineers.

It is important to recognize that InSAR results obtained from this study reflect only the surrogate outcome measure. InSAR technology cannot directly detect cracks in bridge beams or the ongoing corrosion in post-tensioning tendons. It should be emphasized that bridge displacement monitoring using satellite remote sensing should only be considered in cases where a gradual structural deterioration resulting in a measurable and distinct surface expression is expected. In the case of post-tensioned bridge remote sensing, the results would be compared to the estimates obtained from the numerical modeling of progressive tendon failure. The InSAR monitoring approach should be regarded as unsuitable for structures that may undergo sudden and catastrophic failure.

8 CONCLUSIONS

- Satellite-based InSAR technology can be effectively applied to long-term bridge deformation monitoring with mm-range precision, augmenting conventional inspection methods.
- The TerraSAR-X Staring Spotlight mode can provide significantly denser measurement point distribution than the conventional Stripmap mode.
- The results of satellite monitoring over West Point, performed between October 2016 and February 2018, indicate no evidence of permanent bridge deformations.
- The results of this study show that in addition to routine performance monitoring, the Staring Spotlight mode of data acquisition can provide a useful venue for advanced research on bridge deformations.

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10 DISCLAIMER

The contents of this article represent the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The views, opinions, findings, and conclusions do not reflect the official policy or position of the Virginia Department of Transportation or any state or other entity.

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