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Article

Evaluating the damage of collapsed bridges using remote sensing technologies: Case study: Baltimore's Francis Scott Key Bridge

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Abstract: Bridges are vital for linking communities and facilitating economic activity. However, in the face of disaster, like ship collisions pose a significant threat to bridge infrastructure, causing structural damage and potential safety hazards. Rapid and precise assessment of the damage is essential for effective emergency response and recovery operations. Remote sensing with near-real-time satellite imagery provides the disaster scenario. This paper presents a change detection using pre- and post-disaster satellite data for Baltimore's Francis Scott Key Bridge to identify structural damage due to the collision of the ship with support pillars on 26 March 2024. Both optical and microwave satellite data were used from open data sources and analyzed based on geospatial techniques such as change detection and surface profiling. It is estimated that an 1100-meter span of bridge was affected due to this collision, which helped to estimate the damage and mobilize the rescue operations. It may need further validation from ground truth information. Hence, the current study emphasizes the potential of remote sensing satellite data to provide near-real-time impact on disaster analysis.

Keywords: Scott Key Bridge; ship collisions; multi-spectral; optical; SAR; geospatial analysis

1. Introduction

Bridges are vital components of transportation networks, facilitating the movement of goods and people. However, sudden bridge failures lead to loss of human life and economic losses. Traditional damage assessment methods are often time-consuming and pose risks to the surveyors. Near-real-time data of post-disaster scenarios and alerting systems can expedite the emergency response to save more lives. Satellite data has emerged as a valuable tool in assessing the damage to collapsed bridges, providing high-resolution imagery that offers a comprehensive overview of the disaster site.

Researchers have increasingly explored using satellite data for post-disaster assessments, leveraging its ability to capture detailed information on the extent and severity of structural damage. This literature review examines key studies and methodologies in utilizing satellite data for evaluating the damage of collapsed bridges, focusing on the case study of Baltimore's Francis Scott Key Bridge. It is demonstrated the effectiveness of satellite imagery in disaster assessment, using deep learning techniques to analyze flood damage [1]. Their study highlights the potential of satellite data for detecting and mapping structural damage to infrastructure, including bridges, following natural disasters. Research by Jaboyedoff et al. [2] showcases the effectiveness of LiDAR in landslide investigations and suggests its applicability in bridge damage assessment. LiDAR scans provide detailed three-dimensional models of the disaster site, allowing for the identification of subtle deformations and cracks in bridge components. Gonzalez-Jorge et al. [3] discuss using UAVs and artificial intelligence to revolutionize bridge inspection and maintenance practices. Adams and Friedland have explained how pre- and post-disaster image comparisons and object change detection algorithms enable researchers to visualize and quantify bridge damage accurately [4]. Jaboyedoff et al. have studied the Gorkha earthquake in Nepal and demonstrated the effectiveness of this approach in post-disaster damage assessment [2]. Besides optical imagery, SAR can acquire imagery independent of weather conditions or daylight, which plays a vital role in post-disaster assessment. Ehrlich et al. explain how integrating machine learning models with SAR data enhances the accuracy and efficiency of damage assessment [5]. Despite the advancements in satellite data, getting real-time data on disasters with alert-based systems is still challenging. The case study of Baltimore's Francis Scott Key Bridge study can aid in understanding the potential of both optical and microwave remote sensing data for near real-time analysis and assessment of the scenario.

2. Materials and methods

2.1. Study area and data sets

The Baltimore's Francis Scott Key Bridge, located (**Figure 1**) at 39°13′1″ N 76°31′42″ W, inaugurated 47 years ago on 23 March 1977, is a steel arch continuous through a truss bridge that extends across the lower Patapsco River. Comprising two primary spans, supported by an array of concrete piers and steel trusses, the bridge stretches over approximately 1.6 miles (2.6 km). It was operated by the Maryland Transportation Authority (MDTA) and carried an estimated 11.5 million vehicles annually. The bridge and four-lane approaches carried vehicles of all sizes, including many trucks carrying hazardous materials. They formed the outermost of three toll crossings of Baltimore's harbor, including the Baltimore Harbor and Fort McHenry tunnels. On 26 March 2024, at 01:28 EDT (05:28 UTC), the main spans of the bridge collapsed after the Singapore-registered container ship MV Dali lost power [6] and collided with the southwest supporting pier of the main truss section. The evaluation commences by obtaining high-resolution satellite data of the Francis Scott Key Bridge as explained in the flowchart (**Figure 2**). In order to access the damage after the collision and bridge damage, multiple cloud-free datasets were explored using Sentinel-hub for the date range between 18 March and 26 March.

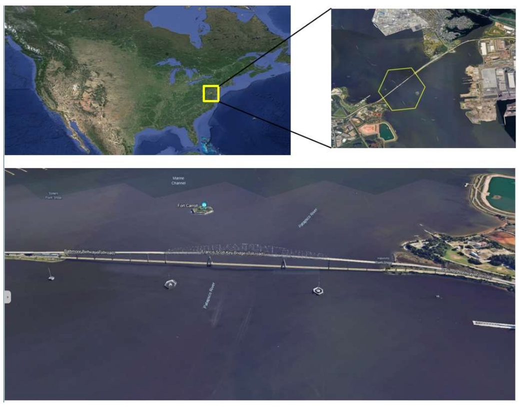

Figure 1. Study area ref (google earth).

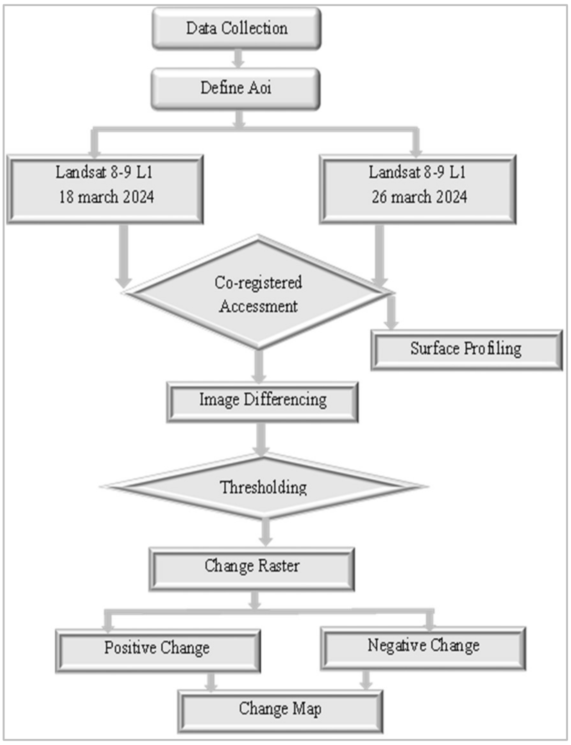

Figure 2. Methodology.

For the pre-disaster, before 26 March, multiple cloud-free data sets were available, but post-disaster, only one cloud-free scene, Landsat 8–9 L1, was available in the open source domain. For this study, pre-disaster T1 Landsat 8–9 L1 dated 18 March 2024 (**Figure 3**) and post-disaster T2 Landsat image 8–9 L1 dated 26 March 2024 (**Figure 4**) are taken into consideration. To further study the area, optical images of the post-disaster scenario were sought; however, due to cloud coverage, the disaster site needed to be visible. VVVH radiometric terrain-corrected Sentinel-1 SAR products from 17 March (**Figure 5**) and 29 March (**Figure 6**) were obtained to address this issue. SAR data offers unique capabilities such as all-weather, day-and-night operation, surface penetration, and high temporal resolution, which are crucial for change monitoring. The high temporal resolution provided by SAR satellites, like the Sentinel-1 mission, enables frequent monitoring of areas of interest, facilitating quantitative assessments of change detection by providing detailed information on surface characteristics. The Landsat 8 and 9 missions, a part of the Landsat program, have significantly enhanced our capabilities to observe and study Earth's surface changes through their L1 level data. The Landsat 8 and 9 satellites have a combined revisit time that significantly improves the temporal resolution of observations made of Earth's surface, offering revisits every eight days at the equator under optimal conditions. Roy et al. [7] and Wulder et al. [8] have explained that improved temporal granularity facilitates more frequent monitoring of changes, which is crucial for applications like post-disaster analysis. Roy et al. have studied that despite better receptivity and swath offered by Landsat 8–9 multi-spectral satellites (bands 2, 3, and 4), challenges such as cloud cover pose limitations to getting post-disaster scenarios [7]. The Sentinel-1 and Sentinel-2 missions are key components of the Copernicus Programme, which is an initiative by the European Union to provide ongoing, thorough, and self-sufficient Earth observation capabilities. First, the Sentinel-2 was explored for the study, but due to cloud cover, the data was not available. Sentinel-1 is outfitted with C-band Synthetic Aperture Radar (SAR) instruments, allowing them to gather imagery regardless of the time of day or weather conditions. A notable advantage of the Sentinel-1 mission is its open data policy, overseen by the European Space Agency (ESA). This policy ensures that Sentinel-1 data is freely accessible to users worldwide, promoting extensive use for scientific research and practical applications. Marino et al. have explained how the availability of Sentinel-1 data (VV and VH polarizations) has spurred innovation in Earth observation, making substantial contributions to areas such as post-disaster analysis [9].

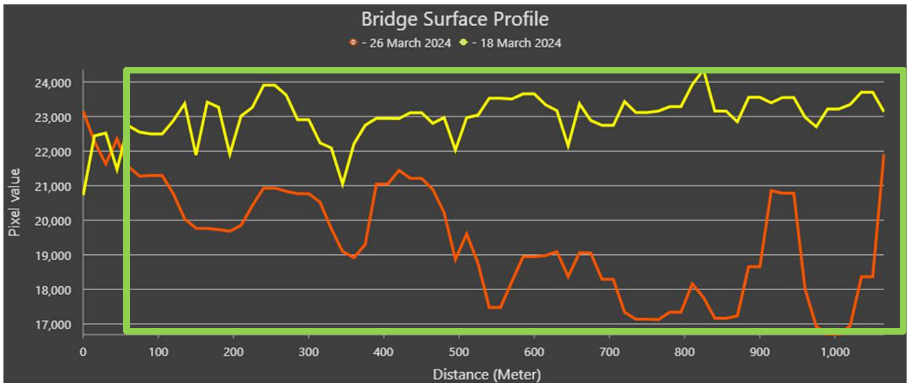

Figure 3. Surface profiling of the pre (18 march 2024) and post (26 march 2024) images.

Figure 4. 18 March 2024—Pre collision.

Figure 5. 26 March 2024—Post collision.

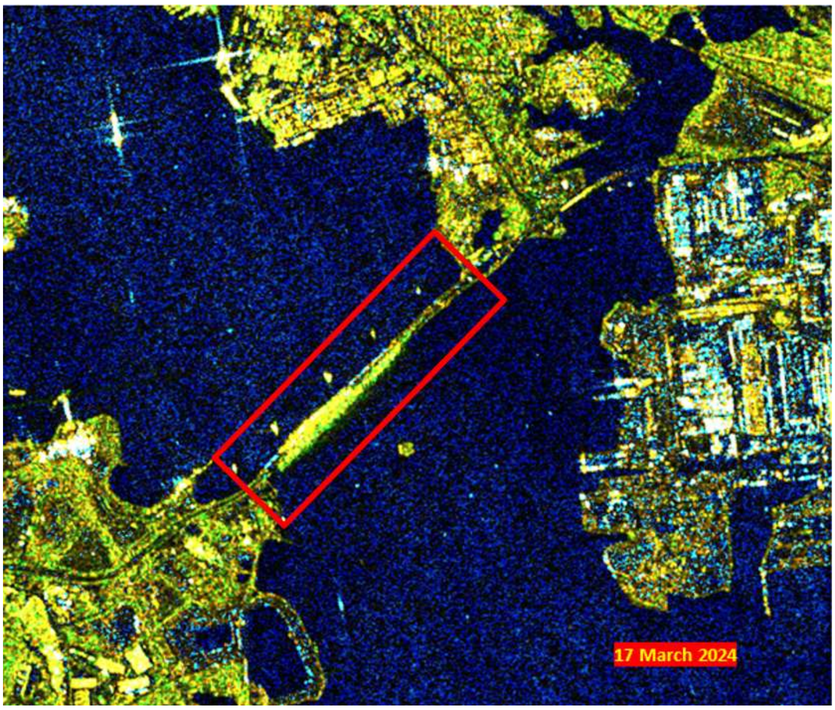

Figure 6. 17 March 2024—Pre collision.

2.2. Methodology

The evaluation commences by obtaining high-resolution satellite data of the Francis Scott Key Bridge in Baltimore on 26 March 2024 (**Figure 2**). To determine the damage's extent and location, pre-disaster images were selected meticulously, considering factors such as clarity, absence of cloud cover, and relevance to the disaster's timeline. Post-disaster images were chosen to closely monitor the event and capture immediate impacts. GIS software was employed to conduct image differencing, classifying changes, and surface profiling based on their intensity and type, as seen in **Figure 4**.

2.2.1. Raster surface profiling

Surface profiling (**Figure 3**) offers a compelling approach to examining surface changes in multi-temporal Landsat image bands 4, 3, and 2 with true color composite. Each pixel within Landsat holds valuable information about reflectance. Extracting surface profiles along the same transect over a bridge can derive T1 and T2 sets of reflectance values. The comparison of these profiles allows for the detection of significant discrepancies, as shown in Chart 1, which may indicate changes in the ground, such as bridge damage. Visualizing these profiles on a graph facilitates the comparison process, unveiling patterns like damage, cracks or gaps, and alterations in the surface. Inherent reflectance information is calculated within each Landsat pixel to extract surface profiles along a defined transect over a bridge at two distinct time points (T1 and T2) to extract surface profiles along a designated transect across the bridge in both T1 and T2 imagery. The extracted T1 and T2 reflectance profiles are then compared to identify potential changes in the bridge structure. Combining surface profiling with other change detection techniques and pertinent data sources can give a clear picture of the changes that happened over time.

2.2.2. Image differencing

Combining surface profiling with the image differencing method provides valuable insights into potential bridges. In this study, the difference in two raster images involves quantifying the changes in pixel values. L1 corresponds to the pre-disaster imagery T1 Landsat 8–9 L1 dated 18 March (**Figure 4**), and T2 Landsat image 8–9 L1 dated 26 March 2024 (**Figure 5**). Pixel values of the first raster image are denoted as T1(x,y) and the second raster image as T2(x,y), where x and y represent the spatial coordinates of the pixels. The change in two raster is calculated by subtracting the pixel values of the T1 from the corresponding pixel values of the T2 raster image. The resulting change value indicates how much each pixel has changed between the two images. Positive values indicate an increase in the surface that is clearly visible as the ship is present at the collision point, while negative values clearly depict the damage to the bridge.

$$\text{Change}(x,y) = \text{T1}(x,y) - \text{T2}(x,y)$$

The change raster (**Figure 7**) shows the damaged bridge's portion as bright pixels showcase the damaged portion of the bridge.

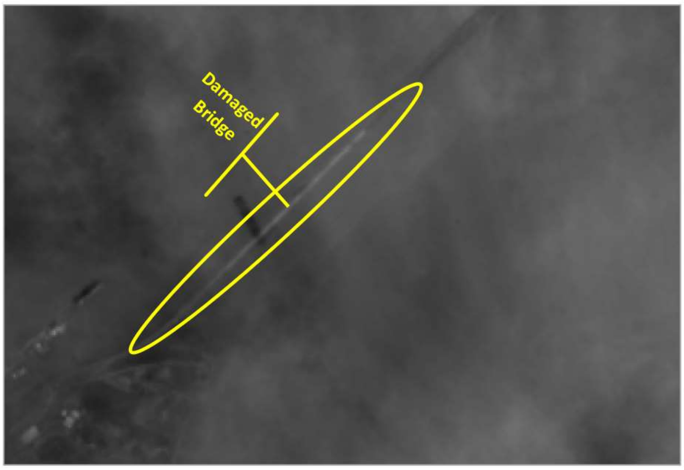

Figure 7. Difference raster ship collision coordinates: 76.5294487° W, 39.2159581° N. Extent of damage to the Bridge: 1100 m (approx.).

2.2.3. SAR data interpretation

To further study the area, optical images of the post-disaster scenario were explored; however, due to cloud coverage, the disaster site was not clearly visible. To address this, a comprehensive investigation of the impact of the bridge collapse was conducted using VVVH radiometric terrain-corrected Sentinel-1 SAR data obtained on 17 March (pre-disaster) (**Figure 6**) and 29 March (post-disaster) (**Figure 8**). VVVH records backscatter in the polarizations of horizontal transmits and horizontal receive (HH) and vertical transmit and vertical receive (VV). Thus, by comparing the VV and HH returns, even little variations in the bridge structure can be found. The high temporal resolution and better spatial resolution provided by SAR satellites, like the Sentinel-1 mission, enable frequent monitoring of areas of interest, facilitating quantitative assessments of change detection by providing finer details of structures. The integration of multi-polarization, high spatial resolution, and RTC enabled the measurable enhancement in calculating the damage assessment. The entire picture of the bridge's state provided by this SAR-derived data clearly highlights the changes and damage to the bridge resulting from the collision. The visual interpretation of SAR data complements the optical analysis, confirming the damage to the bridge with better efficacy and precision.

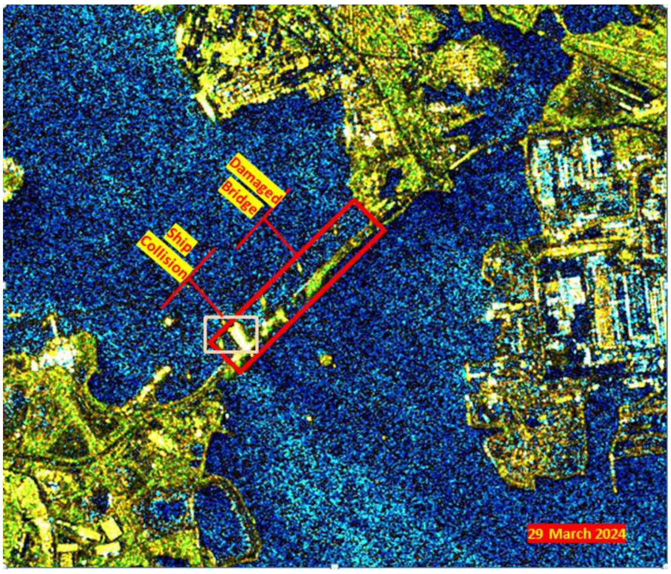

Figure 8. 29 March 2024—Post collision.

3. Results and conclusion

The collision incident in Baltimore has caused considerable damage to the Francis Scott Key Bridge, as indicated by our analysis. By using Landsat 9 L1 True color-pan-sharpened imagery, we were able to identify clear differences between the conditions before and after the collision. In the post-disaster imagery, the absence of the bridge structure was particularly notable. Further analysis through surface profiling and pixel value comparisons allowed us to estimate the extent of the damage to be around 1100 m. The evaluation commenced with the acquisition of Landsat imagery, with the post-disaster image dated 26 March 2024, revealing substantial damage to the bridge structure. Surface profiling using Band 1 highlighted notable differences in pixel values between pre- and post-disaster images, indicating the absence of the bridge in the latter. Optical images from both dates were utilized to calculate the extent of damage, estimated to be approximately 1100 m. This result shall aid various teams involved in decision-making, rescue, and relief operations to quickly assess the damage and mobilize the resources from remote locations, as in making policies for any such event in the future.

To mitigate cloud coverage issues hindering post-disaster optical imagery analysis, VVVH radiometric terrain-corrected Sentinel-1 SAR products from 17 March and 29 March were obtained. SAR data, with its unique capabilities, including all-weather operation and high temporal resolution, confirmed the observed damages and provided valuable insights into surface characteristics. The fusion of SAR and optical data facilitated a comprehensive assessment of damages, highlighting the complementary nature of these datasets in disaster management applications.

Further research is necessary to advance the capabilities of remote sensing technologies in disaster management. Advanced data fusion algorithms and automated damage detection methodologies can improve the efficiency and accuracy of damage assessments. Additionally, the development of alert-based systems for real-time monitoring of disaster events can facilitate proactive response measures, minimizing loss of life and property.

Author contributions: Conceptualization, RS; methodology, RS and SKP; software, RS and SKP; validation, RS, SKP, SJ and KJ; formal analysis, RS and SJ; writing—RS; writing—review and editing, RS and SKP. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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