Outlier Analysis of Bridge Deflections Using Satellite SAR and Structural Simulation: A Case Study on a Collapse Accident in a Water Pipe Bridge in Japan

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ABSTRACT

This paper proposes a method for outlier analysis of bridge deflections using satellite Synthetic Aperture Radar (SAR) and structural simulation based on the finite element (FE) analysis. The proposed method is unique in combining the following two points: (1) detecting anomalous displacement of bridges before a severe accident occurs using satellite SAR displacement analysis, and (2) attempting to estimate the factors anomalous responses on the bridge, such as damages on structural members, using FE analysis. This paper describes the results of the practical application of the proposed method to *MUSOTA* water pipe bridge in Japan, which collapsed on October 3, 2021.

1. INTRODUCTION

Numbers of aging bridges with damages and deteriorations are increasing in many countries. Although, the visual inspection is a usual approach in bridge maintenance; however, it faces difficulties in accurate damage detection unless the inspectors can approach to the damaged structural members exactly. Therefore, development of the structural monitoring technologies and systems to assess bridge integrity is an important issue. As there are various sensing technologies of bridge responses, the authors focus on the displacement analysis of long structures using the remote sensing technology. Interferogram SAR (InSAR) is one of the remote sensing technologies and is a unique method to analyze surface deformation or displacement in a wide area exploiting the phase difference between two complex SAR images. It has been applied to the ground deformation monitoring after earthquakes, landslides, or subsidence. Recently, the structural monitoring of large-scale infrastructure is recognized as one of applications of InSAR (Cusson et al, 2017; Cusson et al, 2021; Selvakumaran et al, 2022). The authors have applied this InSAR technology to analyze the displacement of an existing water pipe bridge in Japan, where a collapse accident occurred in 2021 (The Japan Times, 2021). Here it was found that anomalous displacement occurred only at the collapsed span of the bridge from a year before the accident, and InSAR data might thus capture the precursor to the collapse. In addition, the authors proposed a method to detect anomalous displacement by comparing displacement features within multi-spans of the bridge (Kinoshita et al, 2023). This study demonstrated the possibility of detecting unexpected bridge anomalies before the severe failure occurrence. Detecting the precursors before they lead to severe accidents is one of the great values of the bridge monitoring.

However, there are some issues in the above proposed method. One of them is that the threshold for determining anomalous displacement is determined by the statistical data analysis, which do not directly explain the bridge structural conditions from the viewpoint of structural engineering directly, even though the displacement is a significant physical quantity of a bridge and reflecting its structural properties under certain loading. This study focuses on this issue by proposing to combine the FE analysis with the InSAR data analysis to estimate the factors that cause the observed displacement, thereby revealing the anomalies. The method of analyzing measurement data in combination with the FE analysis is often used with accelerometers which are usually directly attached to the target structure (Nishio et al, 2012). This paper tries it in combination with the remote sensing observation data.

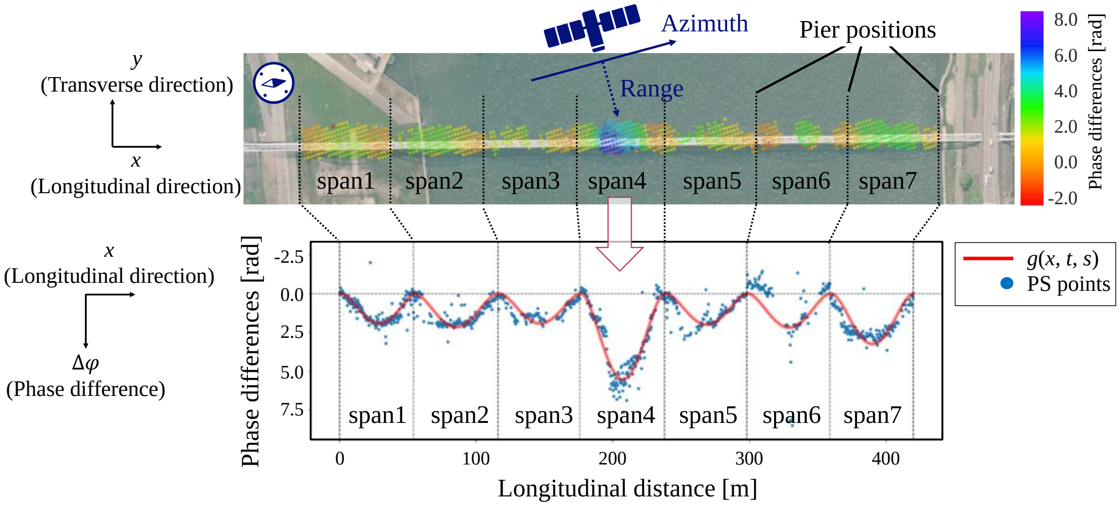

Figure 1. Example of displacement analysis using the proposed method for the data on October 3, 2021. The aerial photo in this figure was created by processing the "Nationwide Latest Photographs, Seamless" in GSI Maps of Japan.

In the following sections, a brief overview of bridge displacement analysis using InSAR data, proposed in our previous study (Kinoshita et al, 2023), is first shown. Then the method for analyzing the displacement data in combination with the FE analysis is explained. Then, an example of the analysis applied to the case of a collapsed aqueduct will be described.

2. OVERVIEW OF SAR DISPLACEMENT ANALYSIS

Here, the proposed method our previous study (Kinoshita et al, 2023) is briefly outlined first. The method analyzes the phase differences along the bridge longitudinal axis. This facilitates understanding bridge displacement trends for each span and the entire bridge. The procedure of the proposed method consists of the following steps: (1) Interferometric analysis, (2) Geocoding, (3) Extraction of persistent scattering (PS) points (Ferretti, 2001) along the longitudinal axis, (4) Data splitting by span, and (5) Mathematical modeling of displacements. Mathematical modeling abstracts the displacement data using approximate curves, even under the noise that sometimes occurs in SAR observations. Since the theoretical equation for bridge deflection is expressed as a quartic polynomial, the displacement data is fitted to a curve using the following equation,

$$g(x,t,s) = \alpha_{t,s} \sum_{i=0}^{4} C_{t,i}\, x^i \qquad (1)$$

where x is the longitudinal distance, t is the date taken of the SAR image, i is the polynomial degree, s is the span number, $C_{t,i}$ is the polynomial coefficient, and $\alpha_{t,s}$ is the amplitude adjustment coefficient. In addition, the boundary conditions shown by Eq. (2) are set to assume that the displacement on the piers is zero.

$$g(x=0,t,s) = g(x=L_s,t,s) = 0 \qquad (2)$$

As a result, a function to represent bridge displacement in each span is obtained, as shown in Figure 1. The parameter $\alpha_{t,s}$ of the displacement function $g(x,t,s)$ is a feature value representing the displacement trend in each span. The statistical difference of this displacement feature in each span makes it possible to detect anomalous displacement. However, it is difficult to estimate the integrity of a bridge based only on statistical differences in displacement features. Therefore, another way to analyze displacement data obtained using satellite SAR is proposed below.

3. PROPOSED METHOD

This paper proposes a method to analyze anomaly factors of bridge displacements obtained by satellite-based analysis. The proposed method focuses on span k , where anomalous displacement is identified, and estimates a factor causing the displacement at the span by combining measurement data and the FE analysis. The flow of the proposed method is outlined below.

(Step 1) Calculate the reference displacement curve $r(x_k)$ based on the measurement data, and calculate the difference $dd(x_k)$ between the displacement curve $g(x_k,t,k)$ and the reference displacement curve $r(x_k)$ at the anomalous span.

(Step 2) Assume damage factors that reproduce $dd(x_k)$ and calculate $dd(x_k)$-equivalent values by the FE analysis.

(Step 3) Compare and consider the anomalous displacement component $dd(x_k)$ and $dd(x_k)$ -equivalent values to estimate potential factors that cause $dd(x_k)$.

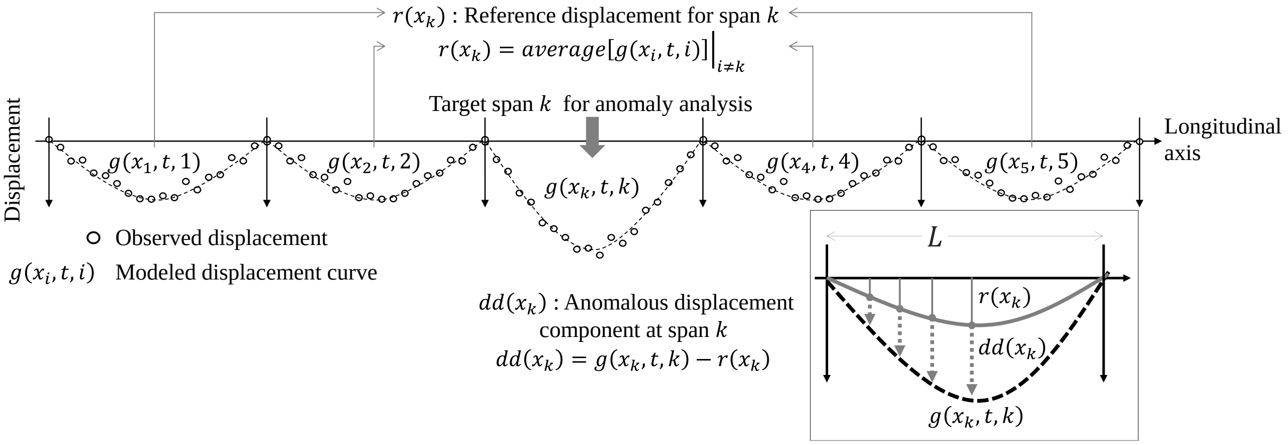

Figure 2. How to calculate reference displacement $r(x_k)$ and anomalous displacement component $dd(x_k)$ at the target span k for outlier analysis.

In Step 1, the reference displacement curve $r(x_k)$ is first calculated using the measurement data obtained using satellite SAR, except for the anomaly span. External forces that may cause bridge displacement may include temperature, wind, traffic, damage, etc. In this method, factors other than damage are considered to contribute equally to displacement over the entire bridge. Damage, in contrast, is assumed to be a factor specific to the anomaly span. Under this assumption, the average value of the displacement curves of spans other than the anomaly span can be regarded as the expected value of the displacement of the factors contributing equally to the entire bridge. That is the reference displacement curve $r(x_k)$. The displacement curves for each span calculated by Eq. (1) are used to calculate the average value. For simplicity, this method assumes that the length of each span is equal. If the lengths differ, Eq. (1) should be normalized by the span length. Furthermore, in Step 1, the displacement component $dd(x_k)$, which is considered to be due to factors specific to the anomaly span, is calculated. The proposed method assumes that the displacement curve $g(x_k,t,k)$ of the anomaly span is the sum of the reference displacement $r(x_k)$ due to factors that contribute equally throughout the bridge and the displacement component $dd(x_k)$ due to factors specific to the anomaly span. Based on this idea, the anomaly displacement component $dd(x_k) = g(x_k,t,k) - r(x_k)$ is obtained by taking the difference between the anomaly span displacement $g(x_k,t,k)$ and the reference displacement $r(x_k)$ as shown in Figure 2.

In Step 2, the displacement of the anomaly span ($dd(x_k)$-equivalent value) that occurs under conceivable damage factors are given is calculated by the FE analysis. Increasing the variation of damage factors and locations makes the FE analysis more difficult. Since different damage factors may give similar anomalous displacements, it is desirable to narrow down the candidate damage factors in step 2. For example, it is possible to narrow down the damage factors by limiting the damage factor to hanger member failure and performing structural calculations by changing the bridge longitudinal location of the hanger member to be failed.

4. CASE STUDY ON A COLLAPSED WATER PIPE BRIDGE

The proposed method is applied to the case study of a collapsed water pipe bridge (The Japan Times, 2021) and evaluated. The water pipe bridge to be evaluated and the satellite SAR data to be used in the analysis are listed in Table 1. In this evaluation, the results of the displacement analysis of the aqueduct by InSAR are presented, the model of the FE analysis of the water pipe bridge is explained, and then the proposed method is applied to the collapsed span. In the case study of the water pipe bridge, it is known from the post-collapse investigation that the collapse was triggered by several hanger members' failure to connect the arch ribs and the main pipe. Therefore, this evaluation focuses on the hanger member failure.

4.1. Anomalous Displacement Component

Like in our previous study (Kinoshita et al, 2023), the 13

Table 1. Specification of the target bridge and satellite SAR data for outlier analysis.

Structural type	Langer bridge
Spans	53.7m x 1, 59.3m x 6
Water pipes	Diameter 0.9m x 2, 3m apart
Satellite SAR	COSMO-SkyMed developed in Italy
Incident angle	20 degrees
Wavelength	31mm in X band
Resolution	3m
Observation dates	13 scenes in total from Jan 2019 to Oct 2021. The reference date is Jan 11st 2019.

scenes of SAR images from January 2019 to October 2021 taken by the satellite COSMO-SkyMed are used. Assuming that the displacement of the center span is known to be more anomalous than other spans by the anomalous displacement detection method in this reference, the proposed method is used to calculate the anomalous displacement component $dd(x_k)$ at the collapsed center span. The water pipe bridge has seven arch spans, all of which have approximately the same structural type and span length. The reference displacement curve $r(x_k)$ is obtained as the average of the displacement curves of the other spans except for the center span, and the anomalous displacement component $dd(x_k)$ is calculated by taking the difference from the displacement curve $g(x_k, t, k)$ of the center span. Furthermore, to make $dd(x_k)$ easier to compare with the vertical displacement calculated in the FE analysis, a simple transformation from the satellite line-of-sight displacement to the vertical component is performed, assuming that the satellite observes the vertical displacement. Figure 3 shows $dd(x_k)$ obtained in this way. In this figure, the anomalous displacement component $dd(x_k)$ starts on August 29, 2020, and expands away from the zero value for the entire span.

4.2. FE Analysis

This section describes the FE analysis of the water pipe bridge for reproducing the anomalous displacement component $dd(x_k)$ in the collapsed span. The FE modeling and numerical calculation were conducted using the 3D structural analysis software *Midas civil*. Here, a FE model of the single-span Langer bridge was constructed according to structural and material properties referenced in the design documentation of the bridge (JSCE, 2022). Figure 4 shows the overall view of the structural model. The main pipes, arch ribs, suspension members, and other members are beam elements, and the simply-supported boundary condition is applied to the span, which is realized by the bearing members. As the load conditions, the live load to the main water pipes, i.e., fulfilled water weight inside the pipes, are applied in addition to the dead load of the whole structure. The demand output of numerical calculation is the distribution of water pipe deflection.

The outputs are then evaluated under various structural conditions with the failures in hanging members, which are represented by delating beam elements at failure locations. In the FE analysis, the 3D displacements of all elements are calculated, but only the vertical displacement of the pipes is used in this study. The value corresponding to the anomalous displacement component $dd(x_k)$ in Figure 3 is indicated as the difference between the displacement in the healthy state with no failed hanging member and that with failed hanging member(s).

The hanging members that were found to be failed due to corrosion by the investigations after the accident are shown in Figure 4 (JSCE, 2022). In the accidents, the failure of the

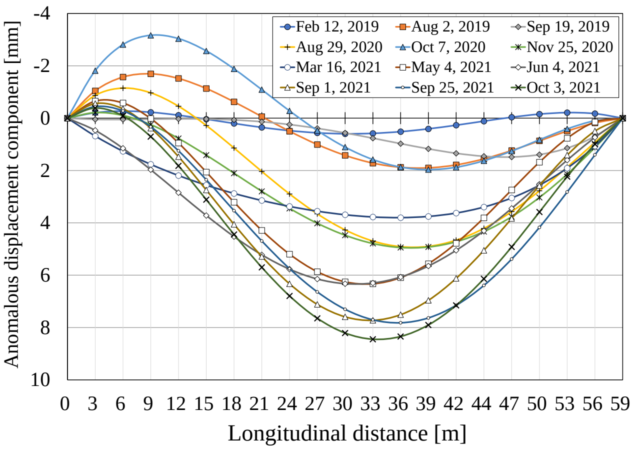

Figure 3. Anomalous displacement component $dd(x_k)$ at the center span calculated from the measurement data.

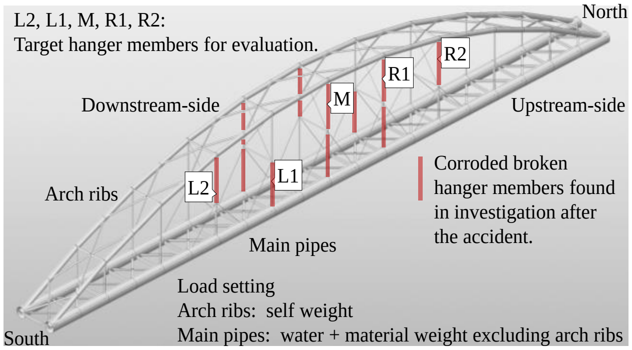

Figure 4. The FE model of the target span and labels of hanger members. Target hanger members for evaluation are labeled as L2, L1, M, R1, R2, from south to north, respectively, which are chosen from among corroded failed ones found in investigation after the accident. Regarding the load setting, arch ribs support their own weight and main pipes support their own weight and water in them.

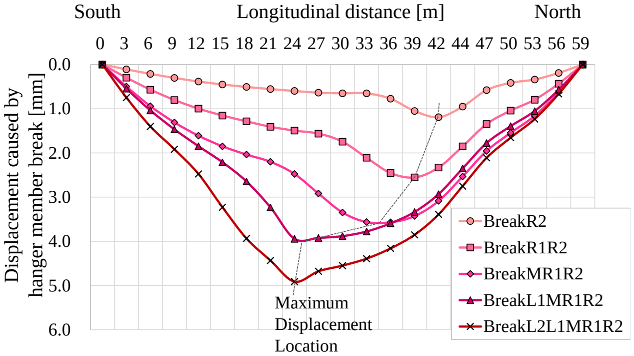

Figure 5. Displacement caused by hanger member failure calculated using the structural simulation. “BreakR2” stands for displacement calculated by the FE analysis when hanger member R2 is failed. Other labels stand for similarly.

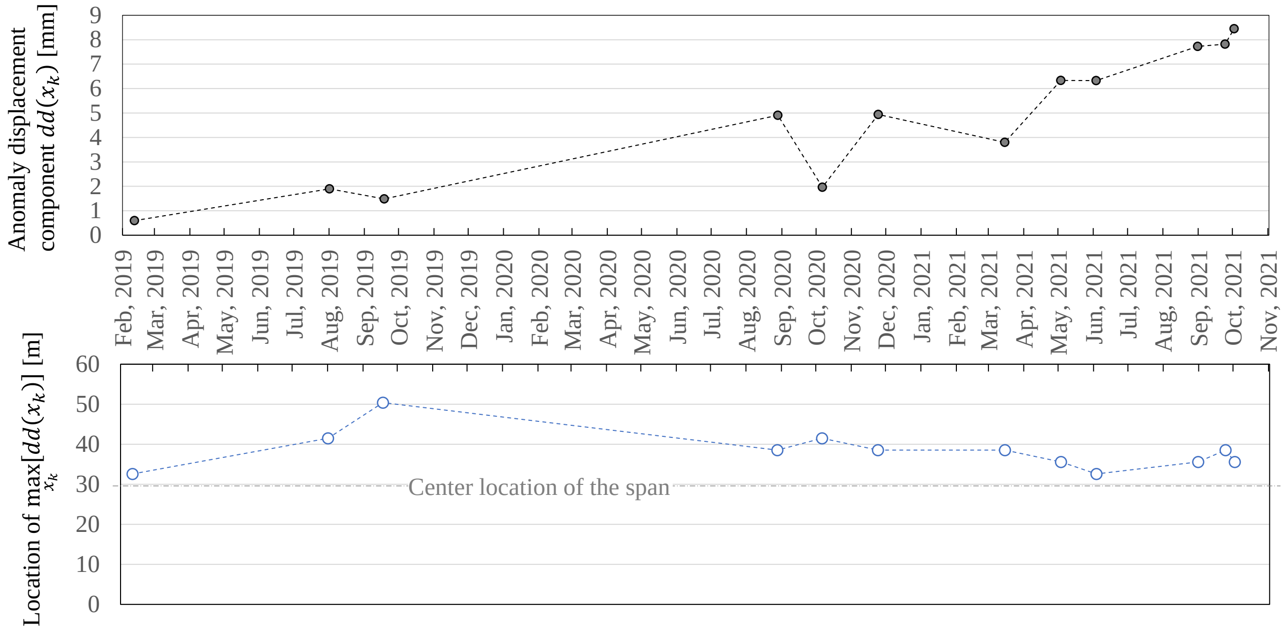

Figure 6. Anomalous displacement component $dd(x_k)$ and its location of $\max_{x_k}[dd(x_k)]$.

top or bottom of the hanging members and the failure of the upstream or downstream members are included. This study focuses on the upstream side of the failed hanging members for simplicity, and assumes that the five hanging members L2, L1, M, R1, and R2 shown in Figure 4 are to be failed. This is because our proposed method focuses on deflection along the longitudinal direction of the bridge, and the longitudinal position of the failed suspension can be considered to have a highly sensitive to this deflection shape. In cases where multiple hanging members are to be failed, the adjacent suspension members are selected to be failed in sequence, starting with the one located at the north side of the bridge.

Figure 5 shows the values corresponding to the anomalous displacement component $dd(x_k)$ in the cases of hanging member failures from 1 to 5. The $dd(x_k)$ −equivalent value increases as the number of failed hanging members increases. As the bridge longitudinal location of the failed hanging members extends from the north to the south, the location of the maximum $dd(x_k)$-equivalent value shifts from the north to the center of the span.

4.3. Comparison between InSAR data and calculated displacements

By comparing the anomalous displacement component $dd(x_k)$ obtained from the measurement data and the $dd(x_k)$-equivalent value obtained from the FE analysis, the evolution of the hanging member failure up to just before the accident is discussed. First, the maximum value of the anomalous displacement component $dd(x_k)$, $\max_{x_k}[dd(x_k)]$, and its transition of the bridge longitudinal locations are shown in Figure 6. $\max_{x_k}[dd(x_k)]$ is located at the center of the span with a value of less than 1 mm in February 2019, but increases slightly and moves to the north of the span in September 2019. Thereafter, $\max_{x_k}[dd(x_k)]$ moves toward the center of the span with increasing values. Comparing to Figure 6, we could make the following hypothesis about the evolution of the hanging member failure.

- As of February 2019, any hanger members would not fail. Because $\max_{x_k}[dd(x_k)]$ is less than 1 mm and located in the center of the span.
- In August-September 2019, the hanging member R2 on the north side of the span would be the first to fail. Because $\max_{x_k}[dd(x_k)]$ is located on the north side of the span, it is close to the failure case of the hanging member R2.
- From October 2019 to March 2021, three hanging members M/R1/R2 would remain failed. Because the bridge longitudinal location of $\max_{x_k}[dd(x_k)]$ changes little.
- The hanging member L1 or L2 on the south side of the span would fail from April to June 2021. Because the value of $\max_{x_k}[dd(x_k)]$ increases and the bridge longitudinal location is closer to the center of the span.

- Other hanging members further would fail after August 2021. It is because the value of $\max_{x_k}[dd(x_k)]$ is increasing further.

Although the above is a hypothesis and the correct answer is unknown, we believe it is a solid hypothesis based on measured data and the FE analysis.

5. CONCLUSION

This paper has proposed a method of analyzing bridge integrity by combining displacements obtained using satellite SAR and structural simulations. The proposed method calculates the anomalous displacement components from the displacements obtained by InSAR technology, calculates the damage factors that reproduce the anomalous displacement components by the FE analysis and compares and analyzes the two to estimate the factors that cause the anomalous displacement. This method was applied to the case of the collapsed water pipe bridge, and a plausible hypothesis regarding the evolution of hanger member failure was discussed.

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