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Differential Synthetic Aperture Radar Interferometry in Monitoring Bridge Deformation Caused by Flood Event

Fathoni Usman[1,3,*], Josaphat Tetuko Sri Sumantyo[2], Herri Purwanto[3], Muhammad Firdaus[3]

[1] Institute of Energy Infrastructure, Universiti Tenaga Nasional, Kajang 43000, Malaysia
[2] Centre for Environmental Remote Sensing, Chiba University, Chiba 263-8522, Japan
[3] Civil Engineering Department, Faculty of Engineering, Universitas PGRI Palembang, Palembang 30116, Indonesia

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ABSTRACT

Many vital infrastructures, which are necessary for society and the economy to function, are heavily dependent in the modern world. Any interruption to such crucial processes can have adverse effects on society. Large transportation networks must be thoroughly inspected, which requires expensive infrastructure management costs. As a result, early signs of challenges can go unnoticed, which could result in disastrous structural failures. In order to evaluate structural safety over time, infrastructure assets must be monitored. Analysing the remote sensing radar data can identify deformation patterns and structural integrity that might endanger a bridge and its users. This study aims to examine the deformations of two bridges by comparing remote sensing measurements taken before and after a flood event, providing insights into temporal changes in bridge structural integrity. The study focused on assessing bridge deformations, encompassing both vertical and horizontal displacements, using radar remote sensing data with differential interferometry while minimising the decorrelation from low coherence of vegetated areas. From the result, the vertical and horizontal displacements were estimated at 30 mm to 40 mm after the flood. The data can be suitable to improve bridge design by exposing elements that cause bridge deformation over time and help assess the damage for priority repairs.

1. Introduction

Assessment and inventory of the condition of highway network infrastructure is a massive challenge to a nation. Sustainable Development Goals (SDGs) indicators encompass critical infrastructure resilience and catastrophe risk reduction. SDG9 and SDG11 are dedicated to enhancing the resilience of built systems by promoting diverse investments to foster the creation of sustainable and secure communities [1]. The availability of infrastructure will be crucial to achieving the SDGs. Transport plays a significant role in connecting populations. In addition, it provides services that enable individuals to be economically productive. The attainment of the SDGs holds the potential to mitigate infrastructure losses and human casualties in the face of natural hazard incidents [2,3].

* *Corresponding author.*
E-mail address: fathoni@uniten.edu.my

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Bridges are amongst the strategic assets requiring a routine assessment to ensure they function as designed.

The conventional approach for evaluating and monitoring the road network infrastructure involves periodic and structural health evaluations on-site. These assessments are conducted to ensure safety and identify specific areas requiring maintenance or retrofit interventions by the designated authority. The conventional methods of supervision are characterised by their protracted nature and their reliance on a significant workforce. These methods have been challenged by difficulties in ensuring the effective operation of many structures and infrastructures that require inspection [4].

There are 18,925 units of National bridges in Indonesia, with 536,585 m total length in 2021 and 84.69% of bridges in stable conditions [5]. The number of bridges with stability issues was 2.89%, 14.02%, 14.68%, and 15.31% in 2017, 2018, 2019, and 2021, respectively [5,6]. The guidelines for bridge inspection are set out in the Road and Bridge Sector Guideline No. 01/P/BM/2022 [7]. The inspection interval after the bridge's construction is annual, with a 5-year maximum interval and adjustable based on risk assessments or bridge conditions [7,8].

Bridge inspectors do structure-specific on-site visual assessments at a low frequency based on inspectors, finances, and support facilities. This technique may not be sufficient for monitoring fast-evolving degradation events and climatic uncertainties causing natural hazards like landslides and floods. Real-time remote monitoring by using in-contact sensors can detect structural safety hazards quickly. Sensors attached to specific locations remotely check for damage, such as high stress over strain changes on crucial structural components, excessive deflections, and vibration [9]. The sensors should function for at least ten years [7]. The equipment, however, is expensive, and the on-site survey activities might be demanding and challenging to accomplish, with a high temporal frequency at the network level. Above all, this is due to financial and administrative budget restrictions [10,11].

The advanced satellite-based remote sensing techniques use interferometry synthetic aperture radar (InSAR) techniques to find changes along the radar sensor's line of sight (LoS). The process is done by measuring the difference in signal phase between images of the same section taken at different times. The distance between the sensor and the ground changes when the object moves up or down, changing the sensor's signal phase. Differential SAR interferometry (DInSAR) led to the development of multi-temporal InSAR (MT-InSAR) methods, including the permanent (or Persistent) scatterers interferometry (PS-InSAR) and the small baseline subset (SBAS), have gained attraction in recent years for monitoring transportation infrastructure systems and investigating the surrounding environment as in [12-17]. Remote sensing from satellites can supplement visual examinations with more objective data collected over large regions and at a much higher frequency. A remote sensing satellite radar can detect small-scale deformations. Successful applications have demonstrated the viability of deploying satellite-based remote sensing techniques in this industry, paving the way for further research and development. In addition, the large area coverage and ability to collect data at a high temporal frequency have helped promote this kind of technology when combined with other monitoring methods [18].

This paper presented the challenges of applying interferometric techniques by using C-band radar data from Sentinel-1 satellite, whereby the static features in the study area are reasonably limited and surrounded by dense tropical forests on hilly terrain. The ascending and descending datasets were collected and analysed to determine bridge displacement. This study aims to examine the deformation patterns and structural integrity that might endanger a bridge using remote sensing methods.

2. Data and Method

2.1 Study Area

Flash floods had occurred in Lahat, South Sumatra, on Thursday, March 9, 2023. The flood hit several areas in Lahat Regency. The flood occurred after heavy rains with high intensity that caused the Lematang River to overflow. The daily aggregated total precipitation based on ERA 5 satellite data at the study area computed in the Google Earth Engine is presented in Figure 1. It shows that the total precipitation was 285.3 mm during the flood event. The flood affected the Tanjung Sirih Bridge and Lematang Pulau Pinang Bridge, connecting Lahat with Pagar Alam and Kota Agung Sub District in Lubuk Sepang. The bridges' locations are shown in Figure 2.

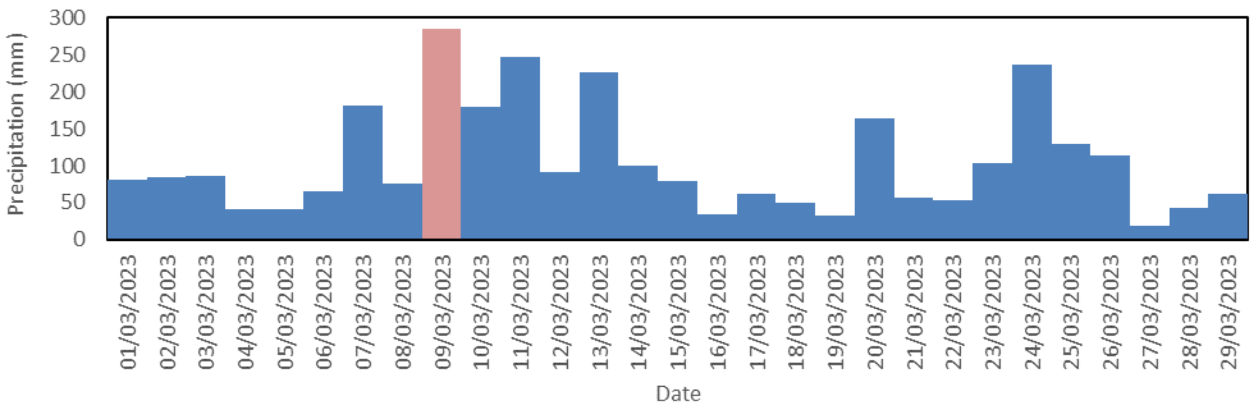

Fig. 1. The daily aggregated total precipitation (mm) in March 2023 in the study area is based on ERA5 satellite data

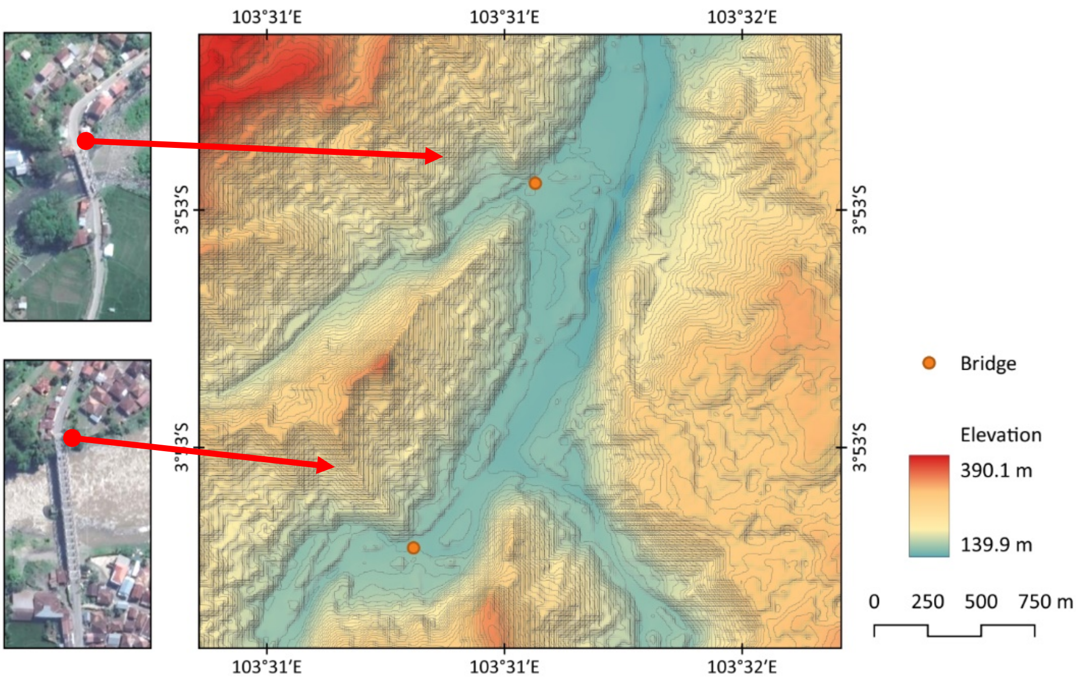

Fig. 2. Location of Tanjung Sirih on the top left and Lematang Pulau Pinang Bridge at the bottom left

The Pulau Pinang District is the nearest to the capital of Lahat Regency, with a distance of 6.1 km, which is the location where the two bridges are studied [19]. The Tanjung Sirih Bridge (Bridge ID: 1502228) is located at Tanjung Sirih Village, Pulau Pinang District. The bridge has only one span with a steel truss for its upper structure. The length of the bridge is 41.9 m, with a width of 5 m, and was constructed in 1991. The second bridge in this study is Lematang Pulau Pinang Bridge (Bridge ID: 1502229), constructed in 1991. The bridge has two spans in steel truss for its upper structure. The bridge's total length is 113 m, and the width is 6 m [20].

2.2 Climate Information

Figure 3 displays the mean precipitation values observed within the designated study area. The period characterised by the lowest precipitation levels is extended from May through August, with June being the month with the least rainfall. Specifically, June recorded a total of 146 mm of rainfall distributed amongst 16 days of rain. The wet season started from September to March [19].

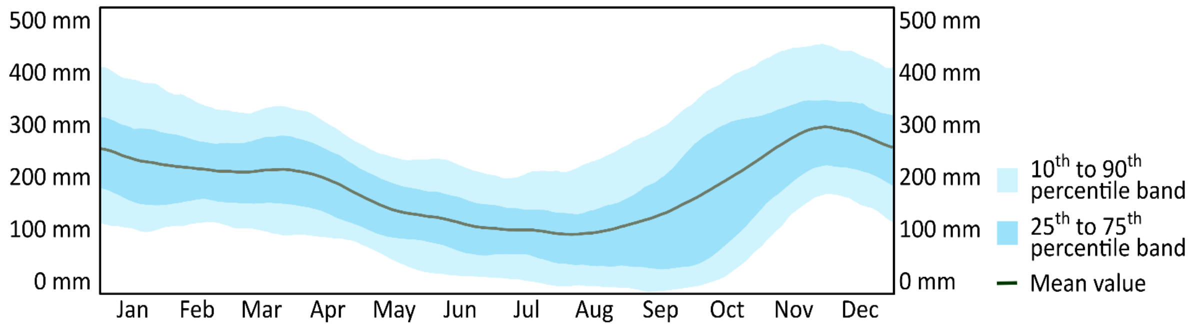

Fig. 3. The annual monthly average of precipitation (mm) in the study area

2.3 Remote Sensing Data

Despite successful applications of InSAR in assessing the displacement of the ground surface, roads, and road infrastructure reaching millimeter accuracy, it is still challenging to allocate information from low-resolution SAR data from C-band satellites (i.e., Sentinel-1) [11]. The challenges came from the tropospheric noise, decorrelation from low coherence of vegetated areas, and rainy seasons in the tropical area [21]. This paper used Sentinel-1 data of Single Look Complex (SLC) data type and IW beam mode in ascending and descending directions.

A perpendicular baseline of less than 150 m is ideal for deformation detection using Sentinel-1 radar data. The smaller baselines offer higher spatial resolution and easier detection of small changes in ground features. However, shorter temporal baselines make interferograms less sensitive to long-term deformation [22-25]. Figure 4 shows the perpendicular and temporal baseline of the imagery data set from multi-temporal acquisitions.

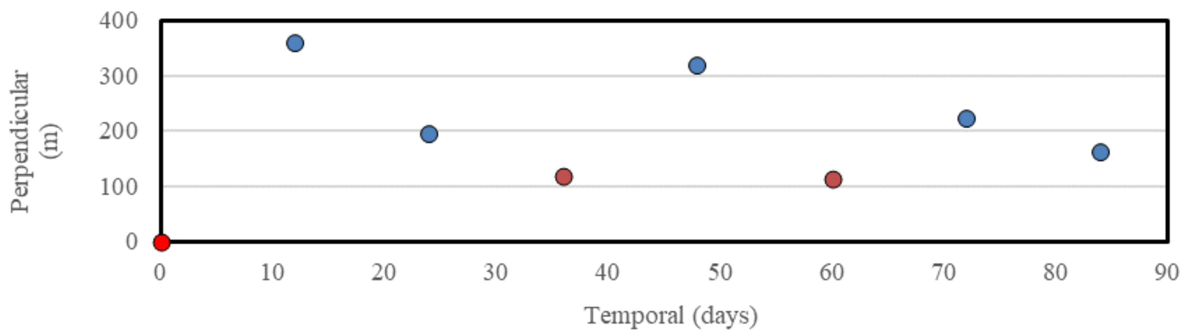

Fig. 4. The perpendicular and temporal baseline of the selected pair is based on radar data acquired on March 16, 2023, from Sentinel-1 satellite

2.4 Method

The master data for vertical displacement was based on the Sentinel-1 imagery acquired on March 16, 2023, the closest available ascending direction data set after the March 9, 2023 flood event. The data set on the dry season was taken based on the acquisition on August 24, 2022. The SNAP Desktop 9.0 was utilised to process the radar imageries data set. Table 1 and Table 2 list the ascending and descending orbit radar data with information on the acquisition date and the baselines. In this interferometric process, the master radar imagery was taken from the post-event of the flood, and the slave imageries were the earlier data. The interferometric product of the phase-to-displacement processes is shown in Figure 5. The process started by selecting a pair of radar imageries with the shortest baseline, applying the orbit file, then the InSAR process, and continued with the DInSAR process [12]. After the InSAR process, the interferogram subsets to the area of interest within the study area based on the West longitude bound at 103.510903, the North latitude bound at -3.898774, the East longitude bound at 103.532925, and the South latitude bound at -3.875142. The primary purpose of setting the tight subset was to minimise the low coherence of the vegetated area. The vertical displacement can be estimated with the following expression as in Eq. (1).

$$\frac{(\phi_{\text{unw}} \cdot \lambda)}{(-4\pi \cdot \cos\theta_{\text{inc}})} \tag{1}$$

where λ = 0.056 for Sentinel-1

The interferometric product of horizontal motion (i.e., East to West direction) was generated from two terrain-corrected unwrapped phases and collocated of DInSAR on ascending and descending orbit radar data [26].

Table 1
Ascending Dataset

Acquisition date	Perpendicular baseline (m)	Temporal baseline (days)
16/03/2023	0	0
08/02/2023	-119	-36
15/01/2023	-112	-60
22/12/2022	-161	-84
24/08/2022	0	0
12/08/2022	-5	-12
07/07/2022	-31	-48
25/06/2022	-88	-60

Table 2
Descending Dataset

Acquisition date	Perpendicular baseline (m)	Temporal baseline (days)
17/03/2023	0	0
09/02/2023	-40	-36
16/01/2023	-79	-60
23/12/2022	-99	-84

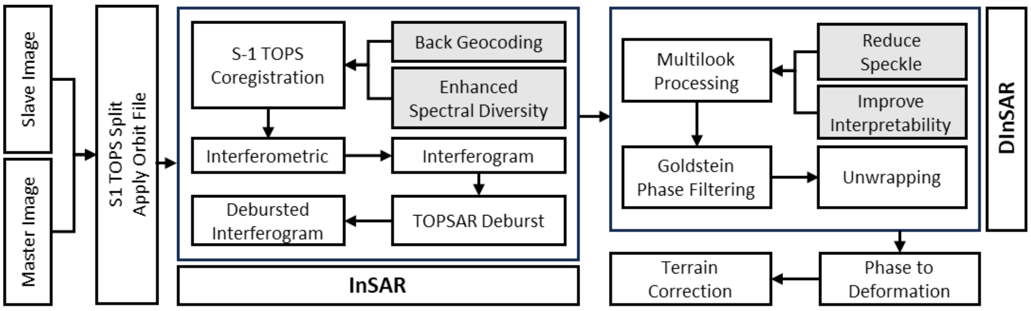

Fig. 5. The differential interferometry processes in SNAP Desktop are used to generate an interferometric product of the vertical deformation

3. Results and Discussion

The processing time on a mobile workstation with 64.0 GB RAM and Intel® Xeon® E-2176M CPU @ 2.70 GHz processor of InSAR was, on average, 25 minutes for four bursts of IW1 sub swath on VV polarisation data. The DInSAR was completed in about 1 second on a small subset of the InSAR data. The unwrapping was completed in 102 seconds. It was resulted that the displacement was detected on both bridge structures after the March 9, 2023, flood event. On the Tanjung Sirih Bridge, which has a single span of 41 m length, the displacement was over 30 mm estimated along the span. The displacement was not observed from June to August 2022 data acquisition. On the Lematang Pulau Pinang Bridge, the maximum estimated displacement was 26 mm. Figure 6 and Figure 7 show the displacement along the bridges. There is a possible scouring of the road to the abutment on both bridges, as reported that the flood reached the road, and the bridge deck issued temporary access closure.

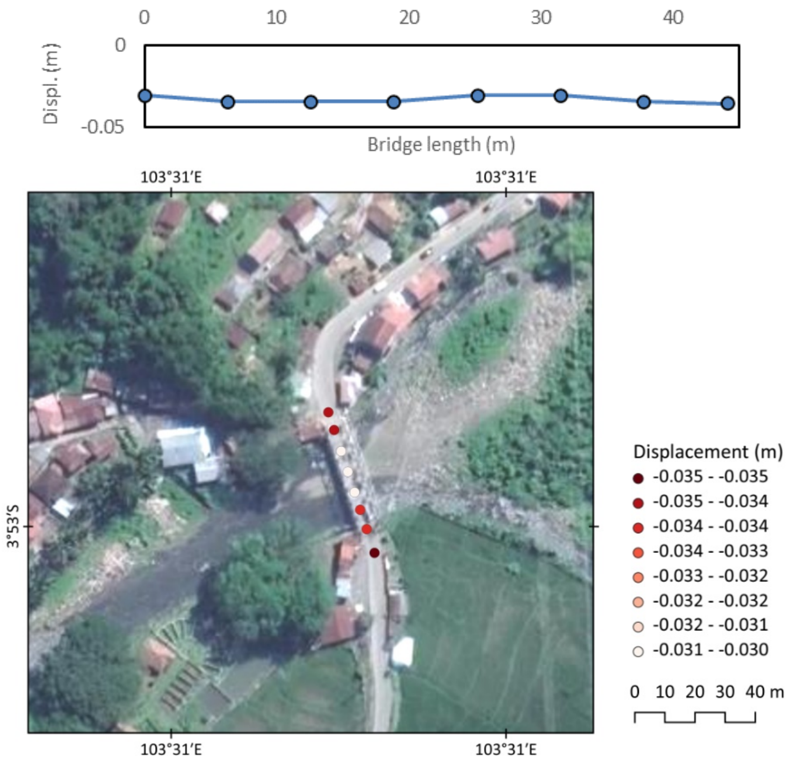

Fig. 6. The vertical deformation of Tanjung Sirih Bridge, which was affected by the March 9, 2023 flood event, is based on the mean value of the interferometric products

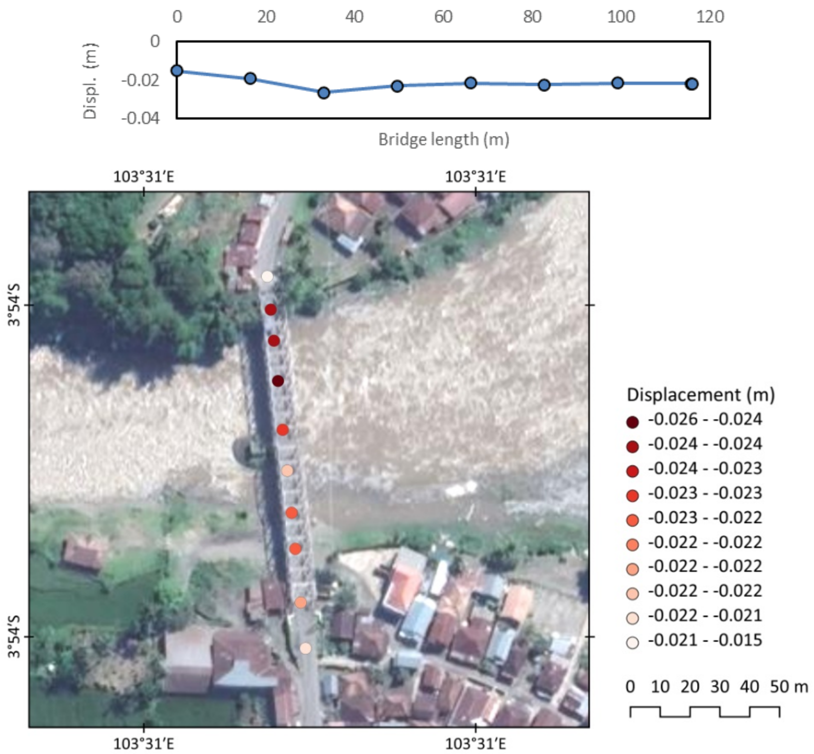

Fig. 7. The vertical deformation of Lematang Pulau Pinang Bridge, which was affected by the March 9, 2023 flood event, is based on the mean value of the interferometric products

Meanwhile, the horizontal displacement from East to West was also estimated on the flood event. Using the angle of incidence θ in the terrain corrected of the unwrapped interferogram on both ascending and descending orbit data, giving the displacement estimation [27]. The direction of horizontal displacement on the bridges is presented in Figure 8. On Lematang Pulau Pinang Bridge, horizontal displacement on the pier area was estimated at 15 mm.

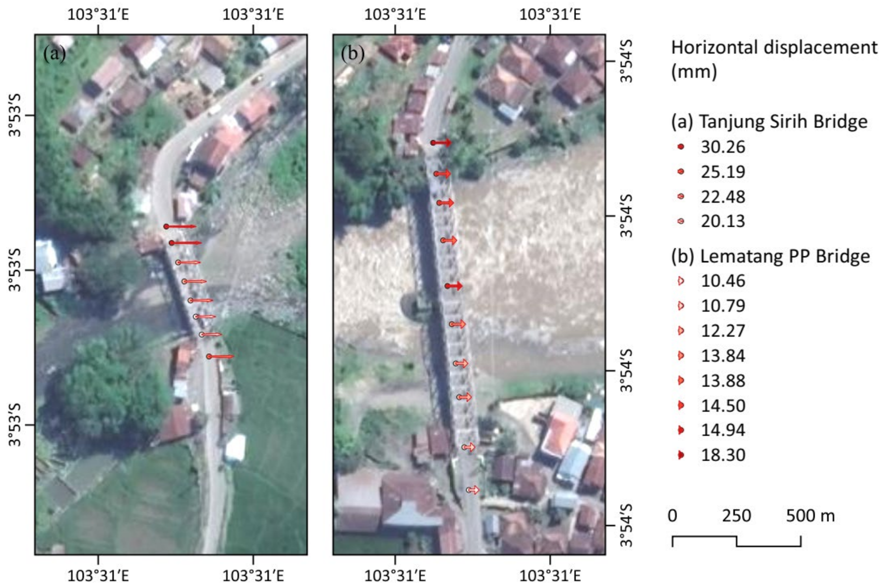

Fig. 8. The horizontal displacement on (a) Tanjung Sirih Bridge with a maximum of 30 mm movement and (b) Lematang Pulau Pinang Bridge with a maximum of 18 mm movement

Based on the time series differential interferometry result, a slightly small deformation occurred on the bridge after the flood event. The deformation pattern on both bridges had shown that the force that impacted the Tanjung Sirih Bridge was higher due to a more narrow stream of the river (i.e., Lim River). Observation of the river's catchment area and possible erosion and landslides that occurred before or in conjunction with the heavy rain during the flood event will give more information on the debris flow and appropriate mitigation to reduce the impact of the flood on the bridge.

The differential interferometry utilising Sentinel-1 C-band radar data resulted in 16 m x 16 m per pixel of deformation after the multilooking and filtering processes. In contrast, the geometrical size of the bridge was relatively smaller. It limits the extraction of information on the observed features. The advantage of using remote sensing data is a large area that covers hundreds of bridges and kilometres of road networks. The challenges were at least two categories: the atmospheric effects over a wide study area and the computational burden [18,22]. In this study, the interferogram subsets minimised low coherence area since the quality and reliability of unwrapped results depended significantly on the input coherence. The differential interferometry technique proved to be a reliable way to determine when significant deformation occurs, showing how well a measure to avoid further deformation initiating failure is going as studied in [28]. However, the method cannot be used on all bridges because of SAR geometry limitations or how the bridges' type and orientation are built [29]. The acquisition of the Sentinel-1 constellation could help minimise these problems by making it possible to get ascending and descending datasets. The continuous acquisition mode allows long-term monitoring plans to be made.

4. Conclusions

Using satellite remote sensing and in-situ monitoring techniques is gaining prominence in structural health monitoring as the demand for forecasting structural instability and ensuring the maintenance of bridges as vital components of road networks continues to expand. This paper presented a method for monitoring the deformation of bridges subjected to flood events using remote sensing. It was found that deformation on the two bridges, about 30 mm horizontal movement along the river stream on Tanjung Sirih Bridge, and about 18 mm on Lematang Pulau Pinang Bridge were observed. The approach utilised the differential interferometry technique of multi-temporal radar data with the interferogram subsets to increase the quality and reliability of the interferometry products. The radar data has several advantages compared to optical remote sensing because it works continuously throughout the day and under diverse weather conditions. The radar data provided extensive coverage, a consistent temporal resolution, and a measurement scale of millimetres. With these advantages, a network of 482 bridges in South Sumatra can be monitored.

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