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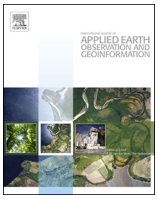

Remote monitoring to predict bridge scour failure using Interferometric Synthetic Aperture Radar (InSAR) stacking techniques

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ABSTRACT

Scour is the removal of ground material in water bodies due to environmental changes in water flow. It particularly occurs at bridge piers and the holes formed can make bridges susceptible to collapse. The most common cause of bridge collapse is due to scour occurring during flooding, some failures causing loss of life and most resulting in significant transport disruption and economic loss. Consequently, failure of bridges due to scour is of great concern to bridge asset owners, and is currently very difficult to predict since conventional assessment methods foresee very resource-demanding monitoring efforts *in situ*. This paper presents evidence of how InSAR techniques can be used to monitor bridges at risk of scour, using Tadcaster Bridge, England, as a case study. Tadcaster Bridge suffered a partial collapse due to river scour on the evening of December 29th, 2015 following a period of severe rainfall and flooding. 48 TerraSAR-X scenes over the bridge from the two-year period prior to the collapse are analysed using the small baseline subset (SBAS) interferometric synthetic aperture radar (InSAR) approach. The study highlights a distinct movement in the region of the bridge where the collapse occurred prior to the actual event. This precursor to failure observed in the data over a month before actual collapse suggests the possible use of InSAR as a means of an early warning system in structural health monitoring of bridges at risk of scour.

1. Introduction

Scour has caused the failure of hundreds of bridges globally in recent decades and is the primary cause of bridge failure in the United States (National Academies of Sciences, Engineering, and M., 2009). In the United Kingdom, the increase in rainfall and flooding events in recent years has exacerbated this problem and contributed to the collapse of multiple bridge structures. Of notable concern from these failures is the loss of human life, or ‘near misses’ which could have resulted in a larger tragedy. Notable examples include the Malahide Viaduct and RDG1 48 River Crane Bridge collapses in 2009, which each occurred moments after the passing of passenger trains (RAIB, 2010; RAIU, 2010). Scour is a natural phenomenon. It can be defined as the excavation and removal of material from the bed and banks of streams as a result of the erosive action of flowing water (Hamill, 1999). This erosive action in the vicinity of bridge piers can lead to the removal of ground material on which bridges are founded, increasing the risk of undermining bridge piers and resulting in collapse. Changes in water flow rates during flooding can make bridge piers particularly susceptible to scour. The collapse of bridges and other structures in or adjacent to water bodies highlights the essential importance in finding new methods to undertake inspection and structural health monitoring (SHM) of bridges to identify precursors indicating signs of impending failure.

Satellite data-based synthetic aperture radar (SAR) interferometry (InSAR) provides a remote means of monitoring millimetre-scale changes over time of multiple discrete points over large spatial areas (Bamler and Hartl, 1998; Ferretti et al., 2001). Early InSAR systems have been used to study large scale deformations (such as earthquakes or volcanoes) but coarse spatial resolutions meant that the imagery was not fine enough to collect sufficient information on single building or infrastructure assets to undertake useful SHM (Massonnet et al., 1994). However, recently deployed SAR sensors in the X-band range are able to collect imagery with a metre, or even sub-metre, spatial resolution. This allows for a number of pixels to cover a single asset and therefore provide information about certain types of asset behaviour (Crosetto et al., 2010; Sansosti et al., 2014). Considering bridge monitoring specifically, the InSAR field of research has considered monitoring

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settlement of bridge piers (Cusson et al., 2012; Del Soldato et al., 2016) and bridge movements to determine thermal expansion and other structural behaviours (Fornaro et al., 2012; Goel et al., 2014; Sousa et al., 2014; Lazecky et al., 2017). The application of InSAR techniques to monitor non-linear infrastructure behaviour that can be applied to bridges is also well documented (Bakon et al., 2014; Lazecky et al., 2015; Qin et al., 2017).

Standard practice for the monitoring of bridges in most countries is to periodically schedule visual inspections, relying on inspectors to be able to spot signs of problems or unusual behaviours before they reach a catastrophic stage. The subjective nature of human judgement is useful to identify non-standard behaviours and to apply a case-specific approach, but previous studies highlight that this does not necessarily provide reliable results (Moore et al., 2001; Bennetts et al., 2016). With regards to bridges that have piers founded within water bodies, such that they are not able to be seen below the water surface, an additional challenge is presented in inspecting foundations to detect scour or other damage. Standard practice is to conduct initial scour assessments at a minimum prescribed time interval (*e.g.* once every three years for UK rail structures), with those highlighted as being at risk having a special maintenance plan put in place, including inspections after major flood events. The traditional method of conducting such inspections is to send divers to visually assess damage. This procedure has several limitations. Diver inspections cannot be undertaken during flood events or during the recession of the flood (due to flow velocity, turbulence or debris accumulation at a structure) when bridges are especially vulnerable (Kirby et al., 2015). Diver safety is put at risk when working in hazardous water environments to look under foundations that could collapse on top of them, and even when a diver or other recording device is sent underwater, it may not be apparent that there is a problem (for example, when loose backfill material hides a scour hole) (The Highways Agency et al., 2012).

Other endeavours in the field of scour monitoring include the development of instrumentation to provide early warning of scour problems. The advantage of fixed equipment over divers is that sensors can provide more frequent readings and thus a more timely warning. Such instruments include single-use devices, pulse or radar devices, buried or driven rod systems, sound-wave devices, fibre-Bragg grating (FBG) devices and electrical conductivity devices, and are described and evaluated in the literature (Lu et al., 2008; Fisher et al., 2013; Prendergast and Gavin, 2014). However, traditional scour monitoring instrumentation often requires expensive installation, maintenance and presence of an external power supply, and can also be susceptible to debris damage during flooding. Often, the interpretation of data from these instruments can be time-consuming and difficult (Highways England, 2012; Prendergast and Gavin, 2014).

Remote sensing through InSAR could overcome many of these issues through monitoring deformations at the bridge surface, above the water line. InSAR provides a means of complementing visual inspections with more objective data, collected over wide areas, and in significantly more frequent intervals than visual inspections (SAR satellite acquisitions are taken in a frequency of days, rather than years). SAR is an active imaging system, and as such can be used both day and night and through cloud cover, thus providing more frequent readings during flooding periods when bridges over water bodies are more susceptible to failure. The large area footprint of each acquisition means that eventually a number of structures could be tracked per frame, rather than installing individual systems on each bridge location.

Employing InSAR remote sensing techniques can provide asset owners with supplementary data which would not otherwise be captured through traditional visual inspections or in the period between inspections, such as millimetre-scale deformations undetectable by eye or the deformation of the ground in the region around the bridge, which may be moving due to unforeseen effects. Studies have shown that InSAR can be applied to monitor anthropogenic effects on infrastructure such as water extraction or mining (Bateson et al., 2014; De Farago et al., 2016) and unforeseen ground movements affecting bridge piers could also be picked up. InSAR can also assist in the monitoring of assets that are difficult to access and not inspected as frequently as would otherwise be desired.

The potential of InSAR to be used as part of early warning systems to identify precursors to bridge failure has been highlighted in work by Sousa and Bastos (2013) which monitors the steady linear deformation of points on a bridge in the years preceding its collapse. The work presented in the paper below is based on a new bridge failure case study at Tadcaster (UK), in which sudden, non-linear deformation in a localised area of a masonry arch bridge is observed in a short period of time prior to the partial collapse of the bridge at this section. Observations and insights of localised areas across the transverse section of the relatively small Tadcaster Bridge (only 10 m wide) are made possible using higher resolution X-band SAR data in the Tadcaster study (from TerraSAR-X rather than C-band Envisat data used in the previous bridge failure study by Sousa and Bastos (2013)). A methodology is presented for the automatic identification through InSAR of uncharacteristic behaviour in the months prior to collapse, which is primarily small millimetre deformation not visible by eye. The application of InSAR data in such a manner provides a means of early warning prior to collapse.

The remaining sections of the paper are structured as follows: Section 2 outlines the case study site and the data used to analyse the failure, as well as the methodology of data analysis. In Section 3, the results of this analysis are presented, which are subsequently discussed in Section 4. The final section draws together the conclusions from this work.

2. Study area

On the evening of December 29th, 2015, following a period of severe rainfall and flooding, the upstream section of the fifth pier of Tadcaster Bridge collapsed into the River Wharfe, resulting in a partial collapse and closure of the bridge (Fig. 1). This closure cut the town in two, resulting in vehicles being required to take a long detour to the next major road bridge and the installation of a temporary footbridge which was installed for the reconstruction period of the collapsed bridge. It also resulted in serious issues concerning utilities, communications and power services (which used bridges as a conduit to cross the river). A gas main was fractured in the collapse, resulting in the evacuation of hundreds of residents.

Tadcaster Bridge is a historic nine-arch masonry bridge over the River Wharfe in Tadcaster, United Kingdom. It is approximately 100 m long and 10 m wide, carrying a single lane of vehicular traffic in each direction and a pedestrian walkway on each side. The present bridge (prior to collapse) comprises two structures of different dates, built side by side to expand the width of the original structure. Documentary evidence (Jecock and Jessop, 2016) suggests it was built from 1698 to 1699 replacing an earlier bridge on the same site that had been swept away by flood. The deck of the 1698 bridge was then raised and its west end widened slightly (probably in 1736 and 1753 respectively), before a second bridge was built alongside it upstream from 1791 to 1792, effectively doubling the width of the river crossing.

Tadcaster Bridge carries a main road and so there is a requirement to undergo a 'general inspection' every two years, and a 'principal inspection' every six years. A general inspection relies on a bridge inspector looking at the bridge from some distance as a "*visual inspection of all parts of the structure that can be inspected without special access equipment or traffic management arrangements*" whilst a principle inspection comprises a "*close examination, within touching distance, of all inspectable parts of a structure*" (The Highways Agency et al., 2007). Flooding events in recent years prior to the collapse meant that the bridge was inspected by divers to detect movement of the river bed that may have resulted in scour.

The failure of Tadcaster Bridge was captured on video as it collapsed. A pronounced dip in the masonry can be seen prior to the pier

Fig. 1. Bridge schematic showing location of bridge and extent of collapse. Photo of collapse site taken after flooding receded. Imagery provided courtesy of North Yorkshire County Council and annotated by authors.

below giving way.

3. Materials and methods

3.1. Data sets

To analyse the deformation behaviour in the period preceding collapse, 48 TerraSAR-X Stripmap mode images(3 m × 3 m ground resolution) taken prior to the collapse in the period from 9th March 2014 to 26th November 2015 were analysed. The final acquisition in November was the last image available prior to the bridge collapse on 29th December 2015. These image acquisitions were taken at 11-day intervals where possible.

LIDAR data produced by the UK Environment Agency was then used in subsequent processing work, giving a much finer resolution of 2 m.

3.2. Methods

InSAR techniques for deformation monitoring exploit the information contained in the phase of at least two complex SAR images acquired at the same imaging geometry (pass direction and incidence angle) at different times over the same area, by forming an interferogram (Bamler and Hartl, 1998; Hanssen, 2001; Rosen et al., 2000). Techniques making use of a stack of multiple SAR images allow the measurement of millimetre-scale movements over a period of time.

Persistent Scatterer Interferometry (PSI) uses reflectors whose response to the radar is dominated by a strong reflecting object and is constant over time and makes use of classical Differential Interferometry Synthetic Aperture Radar (DInSAR) (Ferretti et al., 2000, 2001). It does not impose any constraint on the temporal and spatial baselines of the exploited multi-temporal differential interferograms. The PSI technique relies on analysing scatterers which remain coherent over a sequence of interferograms.

Small Baseline Subset (SBAS) techniques, in contrast to PSI techniques, impose constraints on the maximum temporal and spatial baselines, but also allow the analysis of distributed targets (Berardino et al., 2002; Hooper et al., 2004). The basis of the SBAS technique uses pairs of low-pass filtered (multilooked) DInSAR interferograms. The data pairs involved in the generation of the interferograms are selected in order to minimize the spatial, temporal and Doppler separation (baseline) between the acquisition orbits, thus limiting the decorrelation phenomena.

Both PSI and SBAS techniques were considered for this study to investigate whether a deformation signal in the area of failure could be observed over the bridge prior to its failure. Suitability and application of InSAR stacking techniques to bridges is heavily influenced by the form and geometry of the structure. For example, larger multi-span cable-stayed or suspension bridges can sometimes be difficult in detecting scatterers or understanding where scatterers are coming from. As another example, the metal parapet of concrete bridges can provide good persistent scatterers. A masonry bridge provides less stable reflectors for PSI techniques in comparison with other bridges studied in the literature. In this example, there was one metal lamp post which would likely act as a reflector, which was blocked from the line of sight of the satellite by tree foliage. Thus, no persistent scatterers were derived on the bridge. In contrast, the SBAS technique has been found to be more appropriate for this case, and 8 different distributed scatterer locations across the bridge have been detected.

4. Results

The standard SBAS processing chain (Berardino et al., 2002)

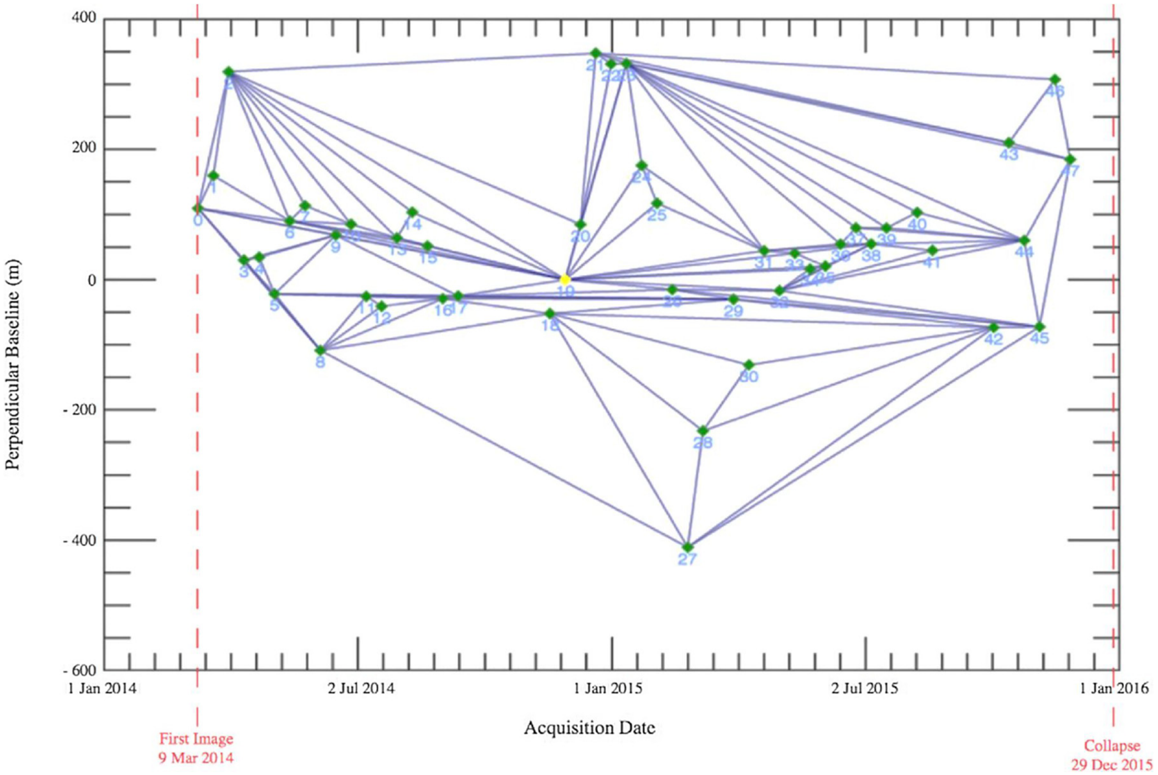

Fig. 2. Temporal - perpendicular baseline for the interferometric stack used in this study. Each acquisition is marked by the green points, with the super master image used being identified as the yellow point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

implemented within the SARscape® software package (sarmap, 2014) has been considered. The temporal and geometrical configuration of the TerraSAR-X acquisitions is shown in Fig. 2. Images were collected over a period of just over 20 months between March 2014 and November 2015. The interferometric processing generated 925 interferograms to identify stable distributed scatterers.

4.1. Deformation map

Tadcaster bridge can be seen spanning over the River Wharfe in the mean SAR amplitude image (Fig. 3). A challenge for end users in the application of InSAR stacking techniques for structural monitoring is the interpretation of what the scatterers physically represent on the asset. Water bodies are often quite easy to identify in SAR amplitude imagery as they feature darker pixels and are incoherent and not picked up by interferometry methods. Conversely, manmade objects with hard (reflective) surfaces are more easily picked up by various InSAR stacking techniques.

In the Tadcaster example, the scatterers pertaining to the bridge are identified as the only points crossing the River Wharfe (seen in the dark pixels on the mean amplitude image, and by the absence of pixels outlining the profile of the river and embankment in the geocoded SBAS results) at the geographical location of the bridge. The presence of another larger road bridge on the A64 motorway can also be inferred further downstream from Tadcaster Bridge on the top left mean SAR amplitude image of Fig. 3.

Deformation maps are commonly plotted as outputs of InSAR analysis to show deformation over time (line of sight displacements as mm per year). This is useful for effects such as the study of deformation in cities after tunnelling or in the steady settlement of structures over time (Erten et al., 2010; Osmanoğlu et al., 2016; Perissin et al., 2012), but in the case of bridge movements and in scour failures such as that of Tadcaster, this representation is misleading. The scatterers on the bridge using this form of plotting are all marked as "steady" with no general trend of rising or falling, due to the assumption that points on the ground will move in a linear trend over time. Simply viewing the deformation map would suggest that there is little to no movement occurring on the bridge. Depending on the structural form and layout, bridges could oscillate in response to a number of load conditions (such as temperature or vehicular loading) or remain largely steady over years with a sudden change in deformation (say in the case of flooding causing localised scour around a bridge pier). It would be more relevant to consider the plot of the scatterers in terms of their movement over time.

The plot of the eight points attributed to Tadcaster Bridge are shown in Fig. 4. The movement detected is the displacement in the line of sight (LOS) of the SAR satellite over time, and is plotted as movement relative to the position of the bridge at the first acquisition, taken on 9th March 2014. The general variation in movement can be attributed to a combination of some real movement of parts of the bridge, and uncertainty within measurement. As discussed below, broadly speaking, this masonry arch bridge should remain roughly steady over time.

The green lines either side of the plotted movements mark the boundary for outliers (the method for which this outlier threshold is identified is detailed in Section 5.2 of the Discussion section of this paper). Points outside of the region defined by the green line are considered as unusual bridge behaviour to investigate.

5. Discussion

5.1. Precursors to failure

As seen in the graph plotted in Fig. 4, the scatterers attributed to Tadcaster Bridge generally, apart from some measurement 'noise', remain steady within ± 2 mm per year for a period of almost two years prior to the collapse. Even after this period, only one region of the bridge (scatterer 'b') diverges from this 'normal' behaviour at 15th November 2015 and 26th November 2015 and can be interpreted as

Fig. 3. (Top left) SBAS results over Tadcaster visualised over the mean SAR amplitude image of the site; (Top and bottom right) SBAS results superimposed over optical image of the bridge area, noting points attributed to the bridge for this study.

exhibiting unusual behaviour of potential concern. Although it is not possible to discern which exact area of the bridge this scatterer area is coming from, in the cluster of scatterers attributed to the bridge, scatterer 'b' is positioned on the upstream side of the bridge deck in the middle region of the length of the bridge (Fig. 3). This directly correlates with the region of the failed pier, which collapsed only on the upstream side of the bridge (the downstream side remaining intact).

The final two movement measurements plotted for scatterer 'b' on

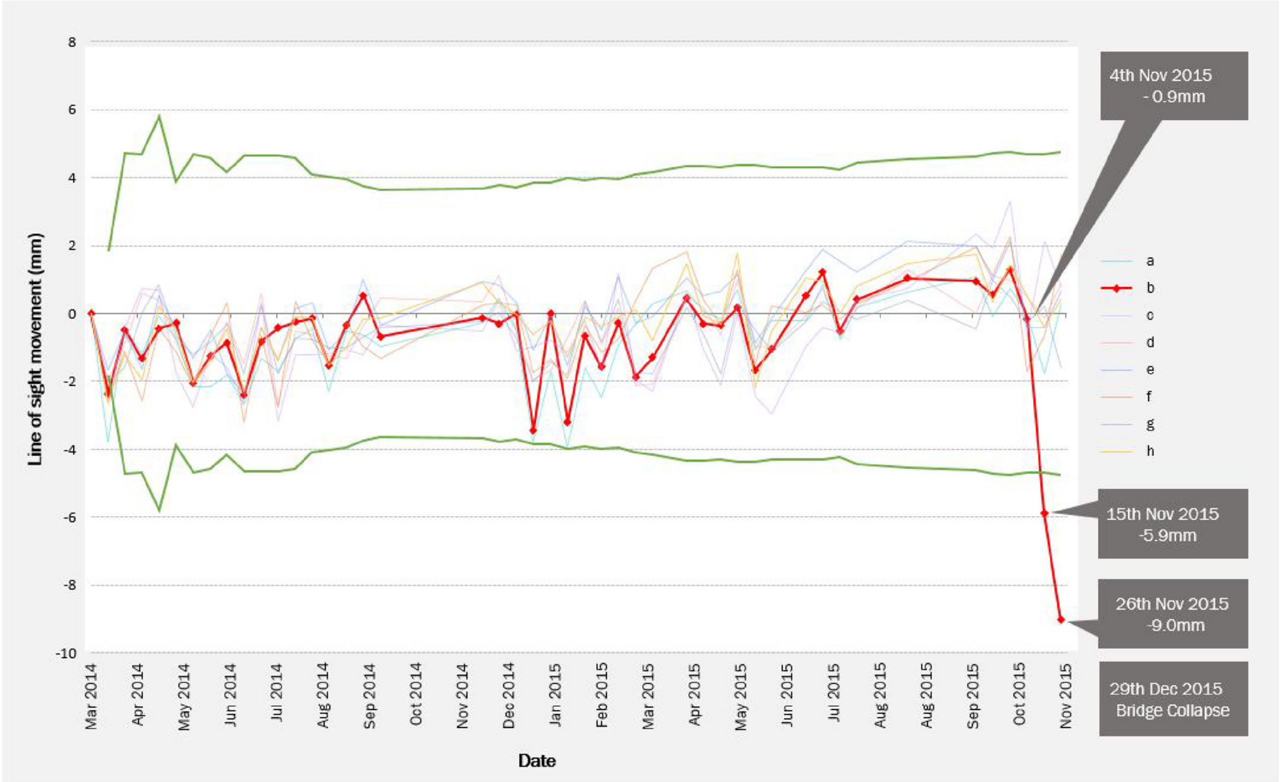

Fig. 4. Movement of scatterers attributed to the bridge plotted over time. The collection of 8 points plotted at a specific time on the x-axis corresponds to a SAR image acquired over the site. The y-axis marks movement in the line of sight of the SAR satellite. The green line marks the boundary for outliers and points outside of this bounded region are flagged as unusual bridge behaviour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

the 15th November 2015 and the 26th November 2015 can be considered as outliers to all other measured bridge behaviour. These dates are the final measurements collected prior to the collapse on 29th December 2015. The significance of these results is that movement suggesting a precursor to failure can be seen in the data one month prior to collapse. As the abnormal movements identified are only of a millimetre scale, they would have been impossible to detect visually in a bridge during any visual inspection undertaken on the same dates.

As previously noted, the final acquisition was taken in the month prior to the collapse, with no further acquisitions available between November 26th 2015 and the collapse on 29th December 2015, where the majority of deformation would have occurred. As such, only a couple of acquisitions identify the localised deformation. The reliability would be improved by further images during this period to confirm the deformation trend.

TerraSAR-X has a wavelength of 31 mm, which limits the maximum observable movement of a scatterer between two observations to 15 mm (the ambiguity), and the direction of movement becomes difficult to distinguish when movement between two consecutive acquisitions is above 7.5 mm. In this example, the movements are less than this value, but an alternative assessment would be required to pick up values that fall outside this range.

In most applications of this technique, deformation detected only on one scatterer would raise questions regarding the reliability of that scatterer. However, the form of bridge failure mechanism must be taken into account. Tadcaster Bridge is a masonry arch which partially collapsed due to scour at the base of the pier. The bridge deformed only very locally at one point-like geographic location which is approximated by one individual scatterer, with the rest of the bridge remaining intact (without deformation). The correlation between the geographical location of the point and the actual failure demonstrates the reliability of that specific measurement point.

5.2. Identification of outliers

To automatically identify outliers for a potential early warning system using SAR data as it is collected and re-processed over time, an approach is required to analyse the processed InSAR time series as it evolves over time. The scatterers represent a time series which can be considered broadly stationary in masonry arch bridges such as Tadcaster Bridge (however, some other bridges types such as large steel and concrete multi-span bridges may have systematic variations that are associated with daily and seasonal temperature change, or other loading effects). Furthermore, for establishing a fully automatic system there are no data points labelled as ‘normal’ or ‘outlier’ available before or during the collection and processing of the data itself. Consequently, the movement behaviour of the bridge must be interpreted specifically for each bridge in an unsupervised and adaptive way.

For the detection of outliers we establish a non-parametric method based on the interquartile range. The interquartile range considers the central 50% of data measurement values (*i.e.*, the values between the first and third quartile) and is related to the median, rather than mean. Considering 1.5 times the interquartile range either side of the interquartile range would identify outliers, with 3 times the interquartile range identifying “extreme outliers” (Tukey, 1977). At each time interval, the interquartile range based on the current and all previous measurements on the bridge, is calculated in a cumulative way and multiplied by three to produce the threshold for “extreme outliers”. Consequently, data is classified as outlier/non-outlier based on whether they fall outside this threshold. The level outside which “outliers” lie (considering all values measured up to the date considered) is marked of on Fig. 4 in green. The final two measurements from scatterer ‘b’ prior to the collapse of the pier lie significantly outside the range of any threshold of 'normal' behaviour, and are successfully identified by the outlier detection process. If this was being considered during monitoring, rather than a retrospective analysis of failure, the identification of the point on the 15th November 2015 would flag that further behaviour should be carefully monitored. This, plus the second data point collected on 26th November 2015, would signal that the asset owner should consider an immediate, more detailed inspection, based on the interpretation of the data. Ideally further points would have been tracked in the period between 26th November 2015 and the collapse to monitor the progression of the failure, but unfortunately no further acquisitions were available until after the collapse date for this example. Data availability looks more promising as time passes, and more frequent acquisitions are becoming available from multiple satellites within the same orbit. The PAZ radar satellite launched in February 2018 in the same constellation as TerraSAR-X, will double the acquisition capacity and halve the revisit time for interferometric applications. More frequent satellite revisit times greatly aids such monitoring applications of critical infrastructure.

A very simple measure to define a range of ‘normal’ behaviour is to consider all points of the processed data set and declaring all instances more than plus or minus three standard deviations from the mean’ outlier’. Three standard deviations either side of the mean contains 99.7% of data instances in a data set (Chandola et al., 2009). This approach reveals a threshold of ± 3.88 mm, and marks the two final points of scatterer ‘b’ as outliers.

5.3. Application to early warning systems

The identification of precursors to failure would make this method of InSAR measurement technically feasible for use as an early warning system. If movements outside a threshold range of ‘normal’ behaviour could be notified to asset owners, there would be the opportunity to send bridge inspectors to investigate if there was indeed a problem with the bridge and, if so, identify the nature of the defect.

InSAR stacking techniques through various methods, such as PSI, SBAS or others as discussed earlier in this paper, would then be applied to all acquisitions acquired to date. The points that relate to the bridge and its movement would then be tracked over time, using outlier detection methodologies, such as that presented here, to identify outliers. Work in combining optical and InSAR satellite imagery for feature extraction including specific consideration of bridges over water bodies (Soergel et al., 2006, 2008; Zhao et al., 2017), as well as research into interpretation of SAR data as specifically applicable to the identification of specific bridge features and behaviours (Qin et al., 2017; Zhao et al., 2017) will hopefully enable better identification of bridge structures within SAR data, and clearer attribution of scatterers to specific areas of a bridge.

5.4. Mapping movement behaviour against environmental data

Scour effects around bridge piers is caused by changing river flow, and in the case of Tadcaster Bridge a change in water flow and behaviour of the river over which the bridge spans can be observed. The River Wharfe had been swollen in the months preceding the collapse, with heavy rainfall starting in late October, continuing through November and December. Data from the UK National River Flow Archive from a site 1.4 km upstream from the bridge (Fig. 5) shows larger river volumes in the winter of 2015, just prior to the collapse. This river gauging station at Tadcaster recorded a peak flow rate of 547 m^3/s during this winter which was the highest ever recorded flow in the period since records began 25 years previously. The severe conditions of persistent high flow would have accelerated scour behaviour, with final collapse on 29th December 2015 occurring after a large flooding event.

6. Conclusions

The results demonstrate the potential of InSAR X-band data to be incorporated into a methodology to detect unusual deformations in

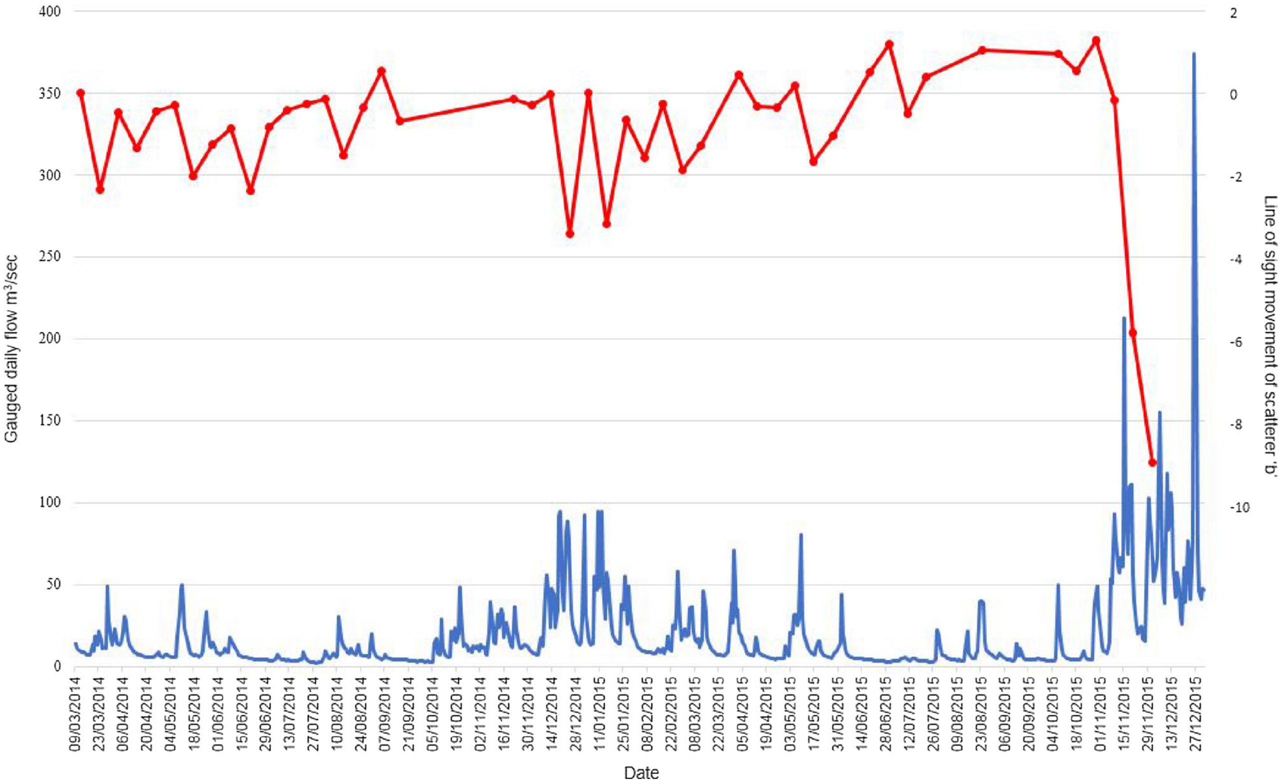

Fig. 5. UK National River Flow Archive data plotting the daily flow rate (blue) measured by a flow gauge in the River Wharfe stationed upstream of Tadcaster Bridge plotted in alongside the progression of scatterer 'b' (red) on Tadcaster Bridge over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

masonry arch bridge structures, with a potential capability to be integrated into structural health monitoring systems as a means of giving early warning of scour failure. To achieve this, InSAR stacking techniques were applied to a stack of 48 X-band SAR images taken over Tadcaster Bridge in a two-year period preceding its partial collapse in December 2015 due to scour failure. Scatterers which could be attributed to the bridge were identified and the movement of these points over time were analysed using outlier detection to identify a region of the bridge that exhibited unusual deformation behaviour. This region matches the region which collapsed one month after this behaviour was identified from the data, and correlates with the flooding period and collapse timeline and mechanism of the bridge due to scour. The prior identification of localised collapse in a bridge structure suggests a promising application in early warning systems, and there would be merit in working to identify further failure case studies and relevant SAR data for study.

The method presented outlines a promising method for detecting precursors to scour failure of bridges, but further work with more case studies and examples should be investigated. One of the key problems with studying failure cases using data is the availability of a suitable quantity of SAR data to enable the processing of a stack over a sufficiently long period prior to collapse. Images must be taken at the same incidence angle, polarisation and direction, and a minimum number of acquisitions are required for InSAR stacking techniques. In order to track behaviour that deviates from 'normal' bridge movement, a sufficient number of data points are needed to determine what the 'normal' behaviour of the bridge is. Although there are many examples of scour failure, there is difficulty in finding a suitable stack of images to process that meets these criteria, and considered acquisition planning must be made for infrastructure at risk.

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