On the potential for using bridge natural frequencies to detect scour: an experimental study

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Abstract

Monitoring bridges for precursors of failure has the potential to improve their safety and resilience. However, the most prominent cause of bridge failure, scour, is difficult to monitor as it occurs underwater. The potential to identify scour by monitoring changes in the natural frequencies of a bridge is studied experimentally in this research. A field study was carried out on a bridge with pre-existing scour confined to a section of a pier foundation, which was monitored throughout a repair process involving controlled backfilling of the scoured region, i.e., scour in reverse. The changes in natural frequency due to backfilling of the scour hole were unable to be captured experimentally as the estimated magnitudes (9% and 6 % for the first and second modes respectively) were of the same order as the variability of the natural frequency estimates. In order to study the relationship between natural frequency and scour in a more controlled environment, a geotechnical centrifuge experiment was conducted to simulate scour in a small-scale integral bridge model in dense sand. The model showed a significant (up to 40 %) change in natural frequency as a result of a scour depth equivalent to 30 % of the piled foundation depth. These experimental findings suggest natural frequencies have shown potential to capture extensive bridge scour, but it may be challenging to capture localised scour limited to only a small portion of a foundation.

Keywords: scour monitoring; bridge scour; modal analysis; natural frequency; vibration-based damage detection; bridge monitoring; sonar scanning; centrifuge modelling

1 Introduction

Bridge scour refers to the removal of soil from around structural foundations located in a river or coastal region due to the erosive action of water [1]. It has been reported as the most frequent cause of bridge failure [2]. Although there are numerous scour monitoring techniques currently available, they have a number of drawbacks related to reliability, durability under rapid water flow during flooding, and the difficulty of providing real-time measurements.

These drawbacks of traditional scour monitoring techniques may be avoided by a recently developed indirect scour monitoring technique. This method correlates the change in support condition due to scour to a resulting shift of certain natural frequencies of the bridge. Previous natural frequency based studies that focused on detecting local damage in the form of cracks (as deep as half a bridge beam or pier) have, at best, indicated fundamental frequency changes of 0,4 % – 7 %, which are unfortunately of the same order as those due to environmental or operational factors [3–8].

Scour, in contrast, is a special damage case – effectively a change of boundary condition – that has been found using numerical modelling [9,10] to cause natural frequencies to vary by double-digit percentages. Although such numerical modelling studies have shown high natural frequency sensitivity to scour, only a limited number of experimental studies have been carried out to validate these findings [11].

This research presents both a laboratory and a field experimental programme to study the feasibility of using changes in natural frequencies to indicate foundation scour.

2 Materials and Methods

A field study was conducted at Baildon Bridge in Bradford in the UK. This bridge was found to have been scoured under part of one pier, and this was due to be backfilled as part of a repair programme. It thus provided a rare opportunity to monitor a bridge in both a scoured and a repaired state (scour in reverse). The bridge ambient vibration characteristics were measured throughout the repair period using a set of accelerometers. The foundation bed profiles were measured before and after repair using sonar scanning to aid numerical modelling. The natural frequency changes due to scour were predicted numerically and compared with measured experimental findings. The initial findings of the numerical modelling and the experimental programme have been discussed in detail in Kariyawasam et al., 2019a and 2019b [12,13].

A laboratory centrifuge modelling experiment was also planned to test a small-scale integral bridge under different scour conditions. Centrifuge modelling is an experimental method used to test small scale models at correct stress levels, thus providing a platform to study full-scale dynamic behaviour changes of the bridge with only a small-scale model [14]. This laboratory study also allowed highly controlled variation of scour hole shapes and depths. Both local scour, involving only local lowering of the bed level, and global scour (lowering of the bed level everywhere) were studied. The effect of water was not explicitly modelled based on the assumption that natural frequency sensitivities would not change due to soil saturation, as shown in Boujia et al. [15]. Details of the experimental setup are provided by Kariyawasam et al. [16].

Although the possibility of replicating the Baildon Bridge properties for a small-scale laboratory centrifuge model was initially attempted, uncertainties in the definition of boundary conditions led to the selection of a hypothetical integral bridge model, where boundary conditions were known and could be modelled more reliably [17].

3 Baildon Bridge Monitoring

The field study was conducted at Baildon Bridge, a three-span road bridge in Bradford, UK carrying the four-lane Otley Road (A6038) over the River Aire. The bridge is a 3 span reinforced concrete structure with overall length of 23m, width of 20 m and skew angle of 23°. It has two bridge piers, each 4,55 m tall, 0,75 m thick and 21,5 m wide. Each pier is supported on a row of 11 piles. These piles are 6 m deep with square cross-section dimensions 0,4 m x 0,4 m. Underwater inspection, together with two borehole records from 1930, identified the soil type up to the pile-driven depth as sandy gravel. The soil was therefore assumed to be medium dense sand with 50% relative density and 1920 kgm^{-3} saturated bulk density.

The bridge had previously experienced scour, mainly near its south pier, after a flooding event in 2015.

3.1 Scour repair programme

City of Bradford Metropolitan District Council planned repair work that involved raising the bed level of the bridge by a maximum of 1,8 m. Sonar scanning was carried out to capture the level of the riverbed both before and after the repair. Figure 3.1 shows two superimposed sonar images from before and after the repair. It shows the scour backfilling of the mid-span of the bridge, especially towards the south pier.

The scour backfilling near the south bridge pier involved 0,6 m of soil, topped by a layer of concrete-filled bags and a concrete mat (Figure 3.2). There was no significant backfilling undertaken below the north pier.

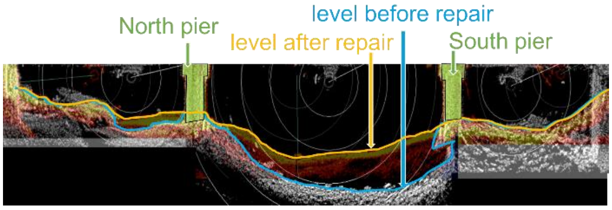

Figure 3.1 Bed profile change due to the scour repair, imaged using sonar scans at the mid-width elevation across the piers

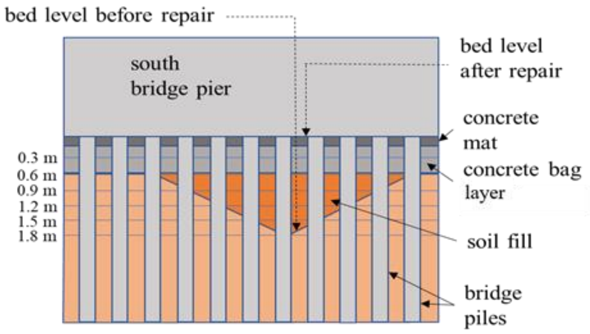

Figure 3.2 Scour backfill proposed below the south bridge pier

3.2 Ambient vibration monitoring

Throughout the scour repair process, the ambient vibration of the bridge was measured using a set of accelerometers and a remote data acquisition system. Ten Epson M-A550 QMEMS accelerometers [18] were deployed on the bridge in the arrangement shown in Figure 3.3. This arrangement was chosen to capture the first bending mode shape, which was found to be scour sensitive according to the initial numerical modelling.

Figure 3.3 Arrangement of accelerometers on the bridge

A custom data acquisition system with a National Instruments CompactRIO-9063 and a Raspberry Pi were used for logging the accelerometer readings at 200 Hz and then transferring these data to a server located at the University of Cambridge.

3.3 Numerical Modelling

The ambient vibration results were compared with numerical modelling for validation. Finite element (FE) models of Baildon Bridge were developed using CSiBridge software (Figure 3.4).

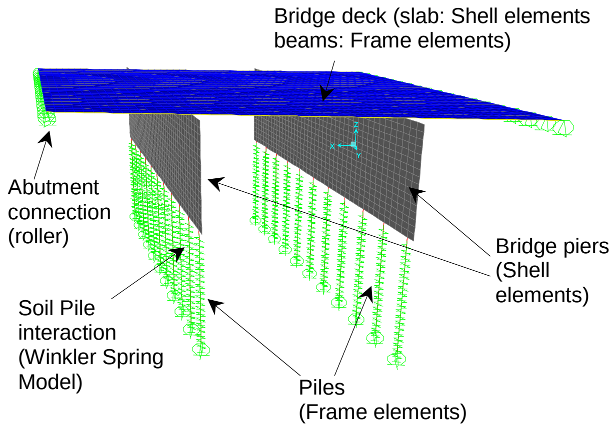

Figure 3.4 Numerical model of Baildon Bridge

The bridge deck slab was represented by shell elements that model both membrane and plate bending behaviour. Bridge deck beams and piles were represented by frame elements, which use a three-dimensional beam/column formulation. Baildon Bridge has deck beams resting on the piers and abutments without any bearings. The deck beam-abutment interface was found to act closely to a roller-support condition, based on the initial numerical modelling [13].

The soil-pile interaction was represented by a Winkler spring model for lateral vibration, and vertical translation at the bases of the piles was restrained. The Winkler model represents the soil medium as a system of discreet, mutually independent, linear-elastic springs. Two FE models were developed with different lateral spring stiffness profiles as shown in Figure 3.5:

FE 1 – a linear stiffness profile based on API design code, assuming small-strain condition[19]; and

FE 2 – a hyperbolic stiffness profile based on Kloeppel and Glock [20] and Seed and Idriss [21].

FE 2 gives a higher spring stiffness than FE 1 over the pile depth of 6 m considered.

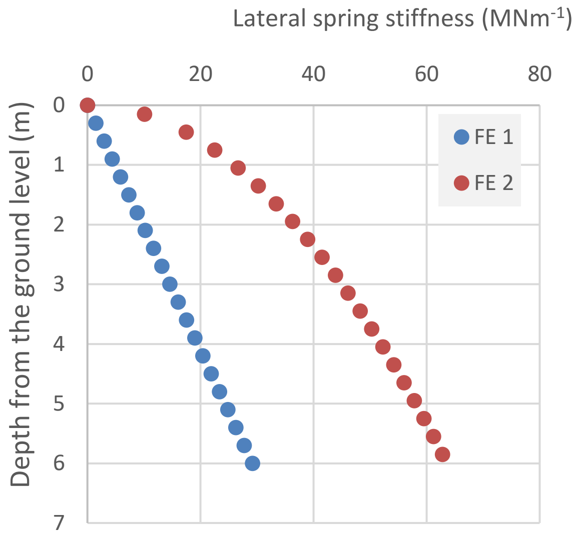

Figure 3.5 Winkler spring stiffnesses used for the two FE models of Baildon bridge

For each scour simulation, a standard linear modal analysis was conducted to determine the undamped vibration modes of the system. The effect of the scour was then simulated by removing the springs at the locations where the scour hole was present.

4 Centrifuge Modelling

Because of the uncertainties in the boundary conditions of Baildon Bridge, it was decided not to attempt to use it as the basis for the centrifuge tests. Instead, a scaled-down generic bridge model was used. Whenever a mass of soil is scaled down by a factor of N, the self-weight stresses also reduce by the same factor. However, the correct dynamic behaviour of soil requires unchanged stress levels when scaling down, as soils exhibit both non-linear stress-strain behaviour and stress-dependent stiffness properties.

Centrifuge modelling replicates field-scale stress levels within a 1: N scale soil model by providing an effective gravity of Ng through centripetal acceleration. Structural models also need to obey other scaling laws, such as mass scaling of $1/N^3$, flexural rigidity scaling of $1/N^4$, area scaling of $1/N^2$ and the system will have resulting natural frequency scaling by N [14]. The scale factor (N) was chosen as 60 for the model used in this study. This scaled-down soil-structure model was tested using the 10-m-diameter Turner Beam centrifuge at the Scofield Centre, University of Cambridge.

4.1 'Full-scale' bridge properties

The scaled centrifuge model was based on a hypothetical full-scale two-span integral bridge with a pile foundation. The abutments were selected to be a flexible support abutment type. These abutments avoid the effects of backfill interaction, by having the piles placed inside sleeves to create a hollow annular space, thus removing the requirement to model the abutment backfill interaction. A span of 15 m was chosen for the bridge deck. The bridge deck has 8 Y1 precast beams at 1,5 m spacing and a 0,2 m in-situ reinforced concrete overlay slab. Each standard Y1 precast beam has a second moment of area of 1,1 x 10^{-2} m^4 and cross-sectional area of 0,31 m^2 [22]. The bridge abutments and piers were assumed to be formed as a pile bent, i.e., a single row of piles. Each pier and abutment has four piles of 18 m in length, 12 m of which is driven into the soil. The pier piles were assumed to be 0,76 m in diameter while the abutment piles were 0,54 m in diameter. At the top of each abutment and deck is a diaphragm beam 1,05 m deep and 1,85 m wide. All full-scale bridge elements were assumed to be constructed of reinforced-concrete (C40 grade concrete) having a modulus of elasticity of 35 GPa and a bulk density of 2550 kgm^{-3} (25 kNm^{-3}). All foundations were assumed to be embedded in a layer of uniform dense sand with 66 % relative density.

4.2 Model scale bridge properties

The full-scale bridge properties discussed above were scaled down to the centrifuge model based on centrifuge scaling laws. The full-scale bridge, having 15 m spans, was scaled down to a 1/60 aluminium model, with 250 mm spans. This aluminium bridge model was simplified to only have two main elements: the piles and the deck. The aluminium piles were circular hollow tubes with 0,9 mm wall thickness. The outer diameters were 9,0 mm for the abutment piles and 12,7 mm for the pier piles. The full-scale composite beam-slab deck was scaled down to a simple aluminium slab deck of 12,7 mm depth. This maintained the required flexural rigidity and mass according to the scaling laws. The integral bridge model was made by fixing the aluminium tubes to the pre-drilled sockets of the aluminium deck plate using high strength adhesive.

This bridge model was excited with an actuator. The mass of the actuator and the accelerometers met the mass scaling law for the total mass of the 1,05 m x 1,85 m diaphragm beams on the full-scale bridge.

All model structures were made from aluminium alloy elements with a Young's modulus of 70 GPa and a density of 2700 kgm^{-3}.

4.3 Experimental setup

The centrifuge package was constructed in an 850 mm diameter steel drum container, which contained the model bridge and soil, as shown in Figures 4.1 and 4.2.

The soil model was constructed with Hostun sand, a high silica (SiO_2 > 98%) sand with grain shape varying from angular to sub-angular. An in-house automatic sand pourer [23] dropped sand at a constant height of 690 mm through a small 5-mm nozzle and gave a 66 % uniform density for the soil sample.

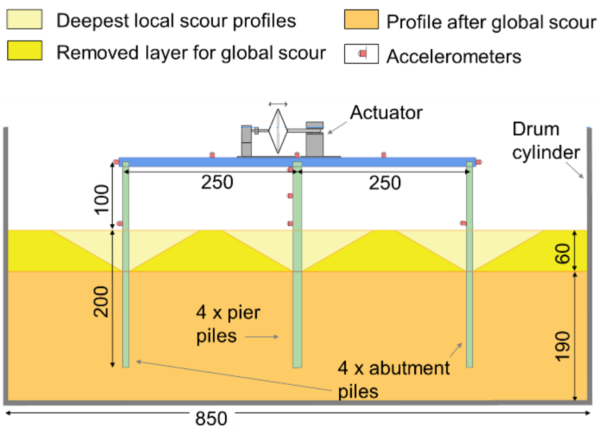

Figure 4.1 Experimental setup: the bridge model and soil in the centrifuge drum container. All dimensions in mm.

The structural model was excited by a piezoelectric actuator at the top, however, the ambient vibration during the experiment was found to be the predominant excitation source. The excitation response was measured at 10 kHz with MEMS accelerometers on the piles and piezoelectric accelerometers on the deck.

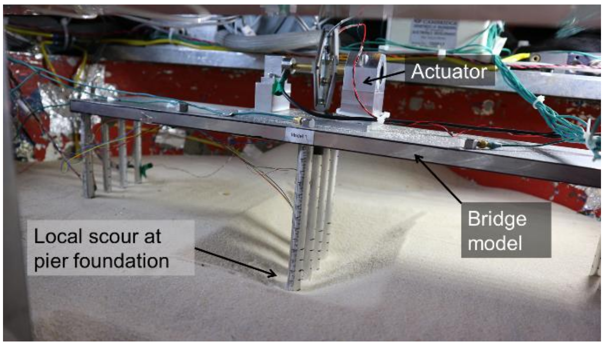

Figure 4.2 Centrifuge model during testing

Progressive scour was studied with three 20 mm steps of local scour: first near the middle bridge pier, then 60 mm local scour near each abutment and, finally, 60 mm of global scour. Centrifuge tests were conducted for each progressive scour case and vibration responses were measured. The centrifuge modelling results are discussed in Section 6, together with the results of the field study at Baildon Bridge.

5 Modal analysis

The modal identification from the accelerometer readings was carried out using Frequency Domain Decomposition (FDD) [24]. The FDD method is based on singular value decomposition of the measured PSD matrix $G_{yy}(f)$ at discrete frequencies f according to Equation (1), where $U(f)$ is a matrix of singular vectors and $S(f)$ is a diagonal matrix of singular values. Over the frequency range associated with a peak in the first singular values, the structural response is dominated by a single vibration mode, with the first singular vector being an estimate of the mode shape and the corresponding first singular value being the auto-PSD of the modal contribution.

$$G_{yy}(f) = U(f)[S(f)]U(f)^T \tag{1}$$

The FDD method assumes that the input excitation is wideband (white noise) and that the structure is lightly damped. Both laboratory and field tests showed the predominant excitation to be random ambient vibration, which can be assumed to provide wideband excitation over the frequencies of the vibration modes of interest. The laboratory centrifuge model showed high ambient vibration during testing, possibly due to the wind created by the rotation of the centrifuge. Baildon Bridge road traffic was also assumed to give a reasonable wideband input during peak-hour traffic. Therefore, the peak-hour period from 4 pm to 5 pm on weekdays was chosen for the comparison of the frequency responses before and after the repair.

The centrifuge model experienced no significant change of temperature throughout the experimental programme. For Baildon Bridge, any effects due to the change in water level or ambient temperature on the bridge dynamics were ignored.

6 Natural frequency as an indicator of scour: results and discussion

Despite using high-sensitivity accelerometers, it proved difficult to track natural frequencies during the field experiment at Baildon Bridge. This was due to a combination of the responsiveness of the bridge (as a relatively massive and stiff structure) and the level of background noise making it difficult to resolve frequency peaks. As shown in Table 1, the first modes (shape shown in Figure 6.1 (a)) of the bridge showed ± 0,6 Hz (13%) variability of the natural frequency estimates, before and after repair. The second mode (shape shown in Figure 6.1 (b)) of the bridge showed ± 0,8 Hz (4%) variability of frequency estimates before the repair, but the natural frequency peaks were not distinguishable after repair due to broadening of the peaks.

The absolute natural frequency estimates of model FE 1 are lower than FE 2. This is expected as the lateral stiffness profiles, previously shown in Figure 3.5, are higher in FE 2. FE 2 showed closer natural frequencies to the experimentally observed mean natural frequencies.

In comparison to the experimentally observed natural frequency variabilities, the FE 1 model estimated the scour backfilling to cause 0,14 Hz (5%) change in the first mode and 0,54 Hz (3%) change in the second mode. FE 2 model estimated slightly higher changes of 0,35 Hz (9%) for the first mode and 1,11 Hz (6%) change for the second mode. Both these FE models have estimated the frequency changes of the bridge to be of the same order of magnitude as the experimental variabilities/errors of observed natural frequencies. Therefore, any possible natural frequency changes due to scour may have gone undetected.

Table 1 Natural frequency and scour relationship of the Baildon Bridge

	Scour case	**FE frequency [Hz]**		**Experiment freq. [Hz]**
		FE 1: API liner	FE 2: hyperbolic	Mode 1
Mode 1	No scour (after repair)	2,91	4,04	4,5 ± 0,6 (13% error)
	With scour (before repair)	2,77 (-5%)	3,69 (-9%)	
Mode 2	No scour (after repair)	16,41	19,84	18,75 ± 0,8 (4% error)
	With scour (before repair)	15,87 (-3%)	18,73 (-6%)	not recognised

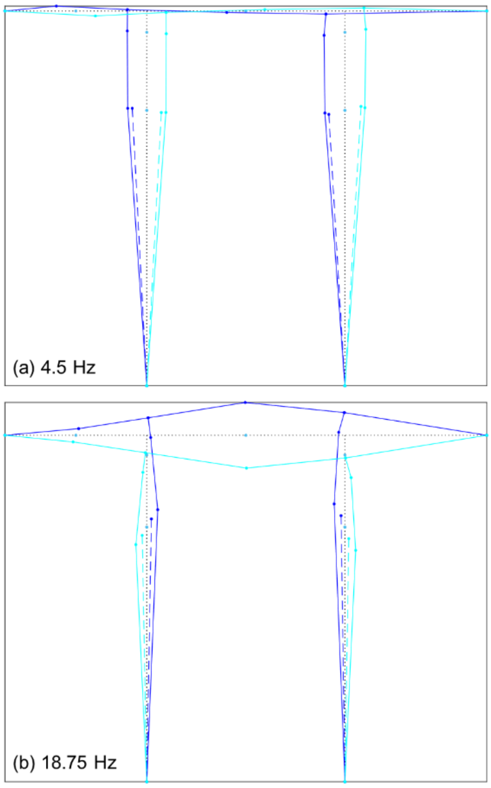

Figure 6.1 Mode shapes of Baildon Bridge

Natural frequency changes observed during the centrifuge tests are shown in Figure 6.2, as representative full-scale estimations and the corresponding fundamental mode shape is shown in Figure 6.3 For local pier scour of 3,6 m, i.e., 30 % loss of pile embedment along the full width of the pier piles, the natural frequency change was 17 %. For the same depth of local abutment scour, the natural frequency change was 14 %.

The frequency changes observed experimentally for 3,6 m of local and global scour in all foundations were 38 % and 40 % respectively. Therefore, there was a slightly lower change in natural frequency due to local scour than due to global scour. Such lower frequency change indicates that the remaining soil surrounding a local scour hole may provide some confining pressure to the underlying soil.

Although natural frequency changes were not detected in the field study, the centrifuge experiments indicated a significant relationship between natural frequency and scour (see Figure 6.1). The changes in frequency are most significant when all three foundations are scoured.

These frequency changes due to scour are considerably higher than the 0,4 – 7 % changes reported in the literature [3–8] for extensive cracking of a bridge beam or pier. Therefore, natural frequencies show far greater potential to monitor scour than to monitor localised cracking.

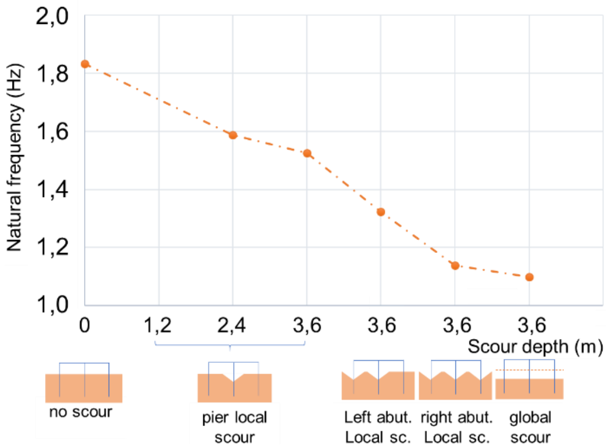

Figure 6.2 Natural frequency sensitivity to different scour profiles tested in the centrifuge

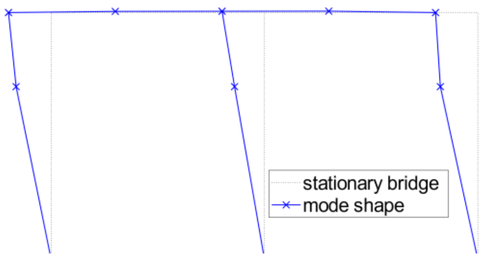

Figure 6.3 Mode shape of the Model 1

7 Conclusions

This paper describes an experimental programme developed to study the potential of bridge natural frequencies to indicate scour. The experiments involved a small-scale integral bridge model tested in a centrifuge, and a road bridge (Baildon Bridge) monitored during scour repair. Based on these experiments, the following main conclusions are drawn:

- At Baildon Bridge, the natural frequency change due to scour backfilling of part of a pier (up to 30 % of pile embedment depth) was not detected due to insufficient resolution of the

measurement system. Measurement errors (of 13 % in the first mode and 4 % in the second mode) were of the same order of magnitude as the frequency changes estimated by two numerical models.
- The integral bridge scour simulation in centrifuge tests captured a 17 % frequency change for local pier scour, and a 40 % change for global scour of 30 % pile embedment depth.
- While natural frequencies have shown potential to capture extensive bridge scour, it may be challenging to capture localised scour limited to only a small portion of a foundation. Further experimental studies are recommended in longer span bridges, which may show higher frequency resolution with ambient vibration as reported in the literature.

8 Acknowledgements

The Laing O'Rourke Centre and Cambridge Centre for Smart Infrastructure and Construction (Innovate UK grant reference number 920035 and EPSRC grant no EP/N021614/1) are gratefully acknowledged for the funding provided to support this research. The PhD funding provided to the first author by the Gates Cambridge Trust is also gratefully acknowledged. The research facilities provided by the Schofield Centre is gratefully acknowledged. We thank our project partners, City of Bradford Metropolitan District Council and TMS Maritime Limited, for their assistance and cooperation. Special thanks to Naveed Anwar, Senior Engineer, City of Bradford Metropolitan District Council, and the TMS scour repair team. We also thank Gaist solutions, DfT and Cumbria Council for providing access to the sonar scanning system, BridgeCat. Data supporting this paper is available from the University of Cambridge Open Data repository [25].

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