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Physical Modelling of Bridge Pier Scour and its Effect on Dynamic Response: Towards Real-Time Monitoring of Bridges

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Abstract: The generation of vortices around bridge piers can lead to removal of riverbed materials from around piers, especially during flood events and heavy rainfalls, which can compromise the stability of the bridge and consequently its failure, if not properly detected and mitigated. Bridge failures pose serious threats to the local socio-economic and public safety and can cost lives. As such, real-time monitoring and early warning systems for scour-induced bridge failure can serve as a vital tool to protect the community and civil infrastructure against disastrous events. Vibration-based monitoring of bridge scour is an attractive option due to its low cost and relatively easy installation without the need to block the road and close the bridge to traffic. While limited number of previous studies have shown the capabilities of acceleration-based monitoring techniques in this area of research, they generally lack a rigorous framework for data analysis within and relating those to evaluate scour. This paper is an attempt to provide such framework that would enable a fast and low-cost analysis of vibration data within a physical modelling study on a simplified bridge pier. To achieve this, three experiments were conducted on an ideal single-pier scaled model bridge in a hydraulic flume, where water flows at a velocity near the critical velocity for the sand bed which in turn generates a scour hole around the pier. Then, the vibration data recorded using two mounted wireless accelerometers, were used to conduct an operational modal analysis through which the natural frequencies are extracted. The extracted natural frequencies and measured scour depths are then used to provide a chart that relates these two parameters. The results of this study showed the promising capability of the vibration-based data analysis in finding this relationship, indicating an up to around 30-50% reduction in natural frequencies as a result of around 50% scour ratio (ratio of maximum scour depth to buried depth), and beyond 50% scour ratio the natural frequencies remain constant. While the data presented in this paper are preliminary, they clearly show a promising potential for application in real-time monitoring of bridge stability under the effect of local scour and further works are underway to enrich the experimental data and empower the proposed methodologies at the laboratory scale.

Keywords: bridge stability; scour; physical modelling; structural health monitoring; modal analysis

1. Introduction

Bridges have a considerably large service life which sometimes reaches or surpasses 100 years, and their resilience against different and rare environmental conditions need to be carefully evaluated. Depending on the size and application of a bridge, its failure can pose a substantial threat to public safety and local infrastructures and civil services. Lagasse, Zevenbergen [1] estimated that in the United States, repairing damages induced by flood alone costs around \$50 million per annum, and that overlooks the consequences of catastrophic bridge failures. In addition, it is estimated that the indirect costs caused by bridge restorations (e.g. long detour and lost production time) is about five times larger than the cost of bridge repair [2]. Cook, Barr [3] has conducted one of the most

comprehensive studies on bridge failure rates and found that the leading cause of bridge failure is scour, accounting for 60% of them. Scour is defined as the removal of the material from bed and banks of rivers as a result of erosive action of flowing water [4, 5]. Scours can be classified into three main categories of “natural scour”, “contraction scour” and “local scour” as depicted in Figure 1a [6]. Natural scour is the natural erosion of the streambed without obstacle due to natural variability of river stream flows and sedimentation regimes, and it takes place on a large scale on the riverbed [7]. Contraction scour occurs due to flow contraction when flow velocity increase as a result of reduced flow cross section (due to bridge abutments, for instance) and it usually takes place within the whole width of river stream. Local scour occurs due to a local concentration of turbulence generated by presence of objects (e.g., bridge piers and abutments) that obstruct the flow of water [8]. Local scour has a smallest influence zone compared to the other two scour types, but it occurs in the close vicinity of the structures and hence it is the most critical. Local scour is mainly caused by horseshoe vortices which is formed due to the downward hydraulic gradient in front of pier as a result of lower dynamic pressure near the bed surface [9]. This results in a downward flow towards the bed and the separated boundary layer rolls up to form a swirling vortex around the pier which then trails off downstream [10]. On the downstream behind the pier, the rotation in the boundary layer over the surface of the pile where shear layers originated from the sides of the pier roll up to form wake vortices [10]. The schematic of these vortices generated around the pier is illustrated in Figure 1b. The combined effect of the horseshoe and wake vortices leads to liquefaction of which allows the riverbed soil to be carried off with current and be deposited downstream which in turn creates a scour hole in front of the pier and a deposit mound behind the pier (Figure 1c). Development of scour hole will then reduce the stiffness of the bridge foundation which can lead to failure of piers [11].

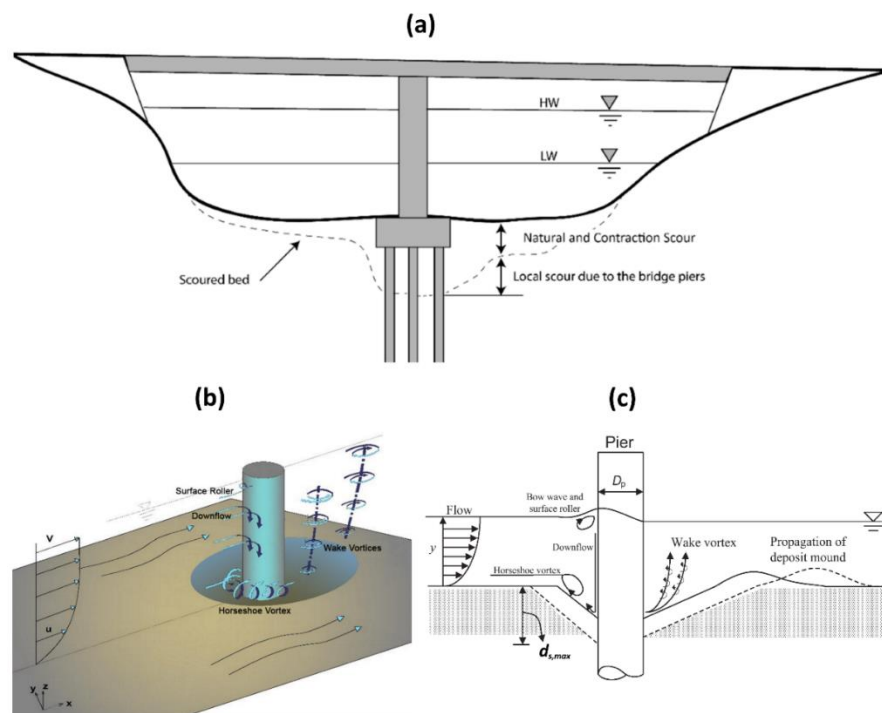


Figure 1. a) definition and general and local scours [8], b) schematic of local scour around cylindrical pier [12], and c) illustration of scour pattern around the pier with maximum scour depth definition, $d_{s,max}$ [after 13].

The formation and characteristics of the horseshoe and wake vortices in the vicinity of the bridge pier has been the subject of extensive experimental research over the last three decades [e.g. 14, 15-21]. Despite the aforementioned studies along with other investigations, precise prediction of scour occurrence and its characteristics and its effect on structural stability of bridges is still difficult [11], mainly due to the spatial and temporal uncertainties associated with characteristics of water flow,

bed materials and structural mechanics and hence most of studies have employed empirical relationships or machine learning [22-27].

The above-mentioned shortcomings with predictive approaches, therefore, highlight the importance of monitoring of bridges to assess their susceptibility to scour and scour-induced instability, which in turn can mitigate the potentially disastrous consequences of bridge failure such as the notable catastrophic events reviewed by Jones and Richardson [28]. Several studies have reviewed monitoring techniques for assessment of scour in bridge piers and abutments [e.g. 7, 11, 29] and have compared their relative advantages and disadvantages and have found that vibration-based monitoring techniques showed promising potential as a cost-effective and precise solution to bridge scour monitoring. This is because sensors used in vibration-based monitoring techniques are easy to install, non-intrusive, very accurate and durable and relatively cheap compared to other types of sensors such as Ultrasonic, TDR (Time Domain Reflectometry), capacitor, and wireless acoustic sensors [11]. However, as Wang, Yu [29] pointed out, the vibration-based modal analysis for bridge scour is still under development and needs further research. The shortcomings with the existing studies in this area is discussed below and then we explain how our innovative approach can overcome these issues.

The vibration-based monitoring of structures is a topic of interest in many civil engineering applications and has recently gained a lot of attention for bridge scour detection. The overall response of a bridge is mainly governed by the soil-water-structure interactions [30] and understanding these interactions can be very complex as many parameters are involved. While predicting the dynamic response of bridges can be quite difficult, measuring the changes in the dynamic characteristics is relatively straightforward. Accelerometers can be placed on bridge pier and their data can be used to detect fluctuations in dynamic characteristics of the bridge [31]. It has been shown that presence of scour hole can significantly change the dynamic response of a bridge pier and more specifically the natural frequency [e.g. 32]. Yao, Darby [32] conducted laboratory scale experiments in a flume, where they showed that the first three predominant natural frequencies of pier (PNF) reduced with increasing scour depth. Briaud, Yao [33] improved upon the previous study by studying the effect of shallow and deep foundation and detected a similar decreasing trend of PNF. Tserng, Ju [34] developed a physical model of 3-pier bridge under extreme flood condition and installed wireless accelerometer to record the vibration response of piers and calculated the natural frequency of each pier. Prendergast, Hester [31] and Bao, Liu [35] neglected the complex fluid-structure and fluid-soil interactions, and conducted experiments on a monopile without the effect of flowing water where the scour was artificially induced by removing soil from around the pile. They also found a decreasing trend for natural frequency as more materials removed from around the pile. These studies, however, only used a Fast Fourier Transform (FFT) on acceleration data induced by an impact hammer and then estimated the natural frequency from the local maxima in FFT plots. Such method of data analysis cannot be easily used for real world bridge environment with a broad range of ambient vibrations. Lin and Chang [36] used velocity sensors to record the dynamic response of piers in a hydraulic flume and to monitor the rigid body motion cause by scouring. However, they introduced an instability index as a diagnostic indicator to evaluate the susceptibility of the bridge to failure instead of a transient evaluation of natural frequency versus scour depth. Mao, Mazzotti [37] conducted field experiments on a bridge using impact hammer and employed an experimental modal analysis to calculate the modal parameters with the known input and output using the Frequency Response Function (FRF). The known input-output algorithms for estimation of natural frequency, require conducting impact tests on the bridge pier and hence cannot be used as a continuous real-time monitoring strategy.

This paper aims to address the above-mentioned shortcomings with the studies listed previously to get a step closer to real-time monitoring of bridge pier scour. In order to achieve that, a physical model was developed where a hydraulic flume filled with sand as the riverbed to ensure the complex fluid-structure and fluid-soil interactions are properly considered (as opposed to studies without flowing water). A scaled single-pier model bridge was buried into soil and a controlled water flow established in the flume to allow steady-state flow-induced scour around pier. Accelerometers were

used to collect the acceleration data of the pier which were then analysed within a novel framework which allows fast Operational Modal Analyses (OMA) with unknown input excitation and using acceleration data of output response through Frequency Domain Decomposition (FDD). FDD [38, 39] had a growing interests in structural health monitoring [e.g. 40, 41, 42]. However, its application in bridge scour identification is limited [e.g. 43] and FFT-based identification of PFN is widely used [e.g. 11, 44, 45], despite its prospects for real-time modal identification.

This paper provides new experimental dataset that gives invaluable insights on the evolution of scour hole under clear-water conditions, while the framework used for data analysis allows the estimation of PNF which can then be related to the measured scour depth. Following the report of the results and their discussion, this paper discusses the advantages and limitations of this study and will provide future research directions for its application in real-time monitoring of scour detection in existing bridges which can lead to early-warning systems for catastrophic failure. In this paper an automatic EFDD method is developed which is capable of extracting the modal parameters of the pier using an output signal only; that is we do not need to have any information about the input excitation and it can even be a white noise. As opposed to the methods used in previous studies which does not provide a precise estimation of PNFs especially for short time intervals, our framework allows conducting an operational modal analysis at much shorter time intervals (5 minutes in this study) with lower number of acceleration data points, and as such this paper is the first to provide the PNFs of piers affected by scours at such small time intervals. In addition, a technique for identification and removal of harmonic components has been employed in data processing which enhances the accuracy and the resolution of the measurements; to the authors' knowledge this has not been used in any studies on vibration-based monitoring of piers. Therefore, the framework introduced in this paper is a novel approach that helps us improve and speed up the identification of changes in natural frequency vs time and/or scour depth.

2. Materials and Methods

In order to simulate the condition of scour development under the river flow regime, a series of flume experiments were conducted at the Western Sydney University's Hydraulic Laboratory. The experimental setup and procedures along with the data analysis methodology is explained in this section.

2.1. Experimental Setup and Procedure

Experiments were conducted in a rectangular hydraulic flume with dimensions of 5000×500×300mm (Length × Depth × Width). The walls are made of Plexiglass sheets with 10 mm thickness. The materials selected to mimic the riverbed materials is a uniform sand with mean particle diameter (d_{50}) of 0.78 mm. The water is supplied with a circulating pump system and the flume is equipped with a flap gate valve at the downstream that regulates water discharge to set the water level to a desired depth. A pier made of a PVC pipe with an outer diameter of 25 mm buried into the sand to a depth of d_b and its top end was attached to a straight board to simulate the bridge deck. The pier diameter was chosen to follow Melville and Coleman [5] where they recommended that the ratio of pier diameter (D) to the width of flume (W) needs to be greater than 0.1 in order to minimise the effect of contraction on scour depth. The schematic of the experimental setup and dimensions of the physical models are depicted in Figure 2.

To avoid the effect of water depth on local scour depth, the ratio of pier diameter to water depth ratio should be less than 0.7 according to Melville and Coleman [5]. As such, the depth of water in this study was chosen to be 100 mm. In order to prevent live bed scour condition (where bed particles are transported by the flowing water and hence filling the scour hole), the water flow rate was chosen to be smaller than a critical velocity which mainly depends on water depth and particle size [46]. This critical velocity for the experimental setup in this critical velocity was estimated to be 0.333 m/s after Melville and Coleman [5] and hence a mean water velocity of 0.33 m/s (equivalent to a volumetric flowrate 9.9 litre/s) was chosen in this study. The mean water velocity is chosen close to critical

velocity to facilitates the local scour development under clear water condition and hence replicates the condition under high river flow conditions such as those following extended heavy rainfalls.

The first step of the test was to install the pier at the centre of the flume. After that, the bed materials were placed and levelled, hence the pier can be considered as a free-standing (floating) pile. Then the flume was slowly filled with water from downstream, ensuring the sand bed was not disturbed. Once the depth of water reached the target depth of 100 mm, the upstream flowrate was gradually increased to the design rate of 9.9 litre/s while flap gate valve was adjusted to maintain the water depth of 100 mm. The experiments were run until the maximum scour depth reached to 90-95% of the pier's burial depth (d_b).

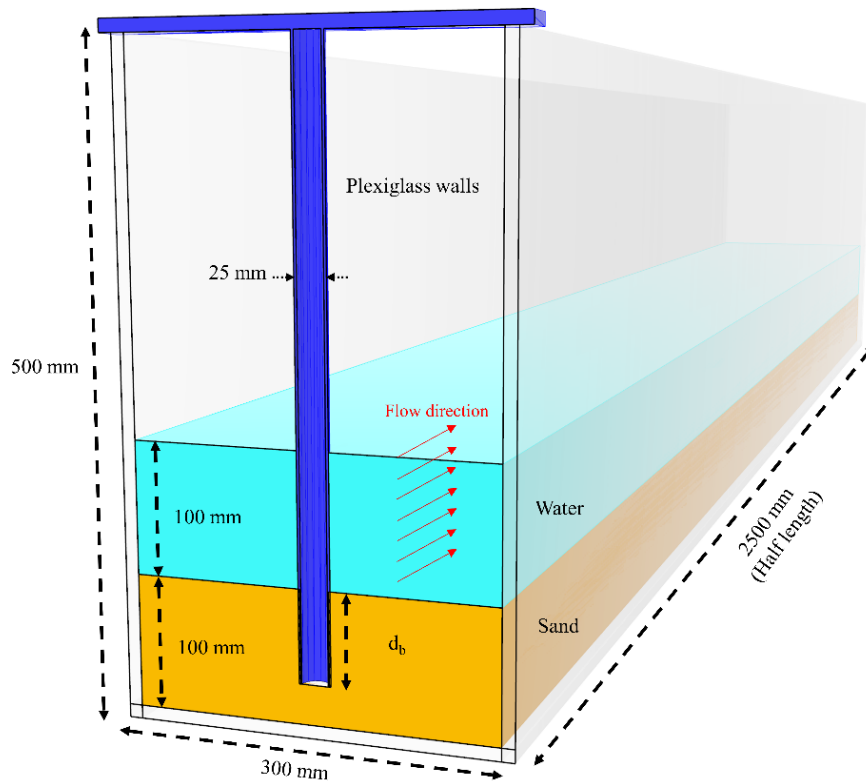


Figure 2. schematic of the hydraulic flume and model pier used in the experiments (section view at the half length).

In order to measure the maximum scour depth, a laser range finder was mounted on the front side of the pier (upstream) whose data are recorded every few minutes. Care was taken to ensure that the rangefinder emits light perpendicular to the water surface to minimise the backscattered light off the water surface. The rangefinder provides an accurate estimation of the distance from the sensor to the surface of the sand bed (± 0.2 mm) and its changes represent the instantaneous maximum depth of scour hole. Two wireless accelerometers were also mounted on the back side of the pier (downstream) which record the accelerations in the flow direction at a frequency of 124 Hz. One of these accelerometers is located at the top of the pier near the bridge deck and the other one is mounted level 7cm of the pier surface.

The accelerometers store data on their dedicated memory on specified time intervals which will be used for FDD analysis upon completion of the test. Figure 3 shows photographs of the hydraulic flume, its pump, and instruments mounted on the pier during testing. It should be noted that throughout the test, some vibration was forced to the deck to simulate the effect of ambient vibrations such as those in real bridge environment (e.g. due to passing vehicles and trains).

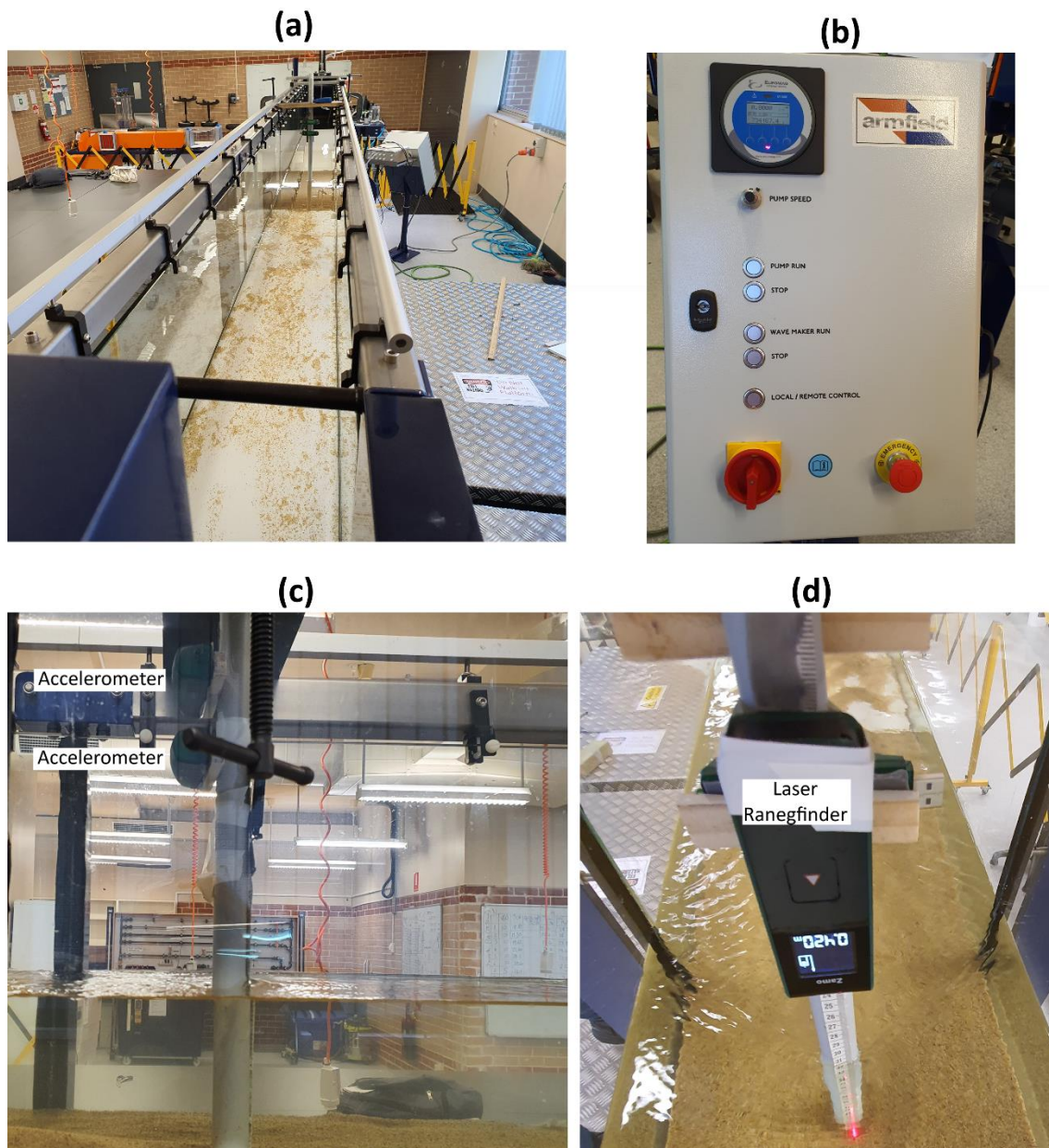


Figure 3. the hydraulic flume and model pier, and utilised instruments: (a) the photograph of the hydraulic flume, (b) the control panel of the pump, (c) two accelerometers mounted on the pier, and (d) the laser rangefinder mounted on the upstream side of the pier.

2.2. Scaling Laws for Physical Modelling

In the current physical modelling technique, Froude number similitude is chosen because the local scour near the bridge pier usually occurs in open channel flow. Since the flume provides an open channel, the flow is governed by the balance between inertial and gravitational forces and the ratio of these forces is called the Froude Number as shown in Equation 5 [47]:

$$Fr = \frac{V}{\sqrt{g \cdot h_w}} \quad (1)$$

where, V is the water velocity, h_w is the water depth, and g is the gravitational acceleration. Studies have shown that the effect of Reynold's number similitude can be negligible in scouring applications owing to its relatively high value, i.e. turbulent flow [5, 47]. With Froude number similitude, the following scaling relationship can be written

$$V_r = \sqrt{L_r} \quad (2)$$

$$t_r = \sqrt{L_r}$$

where L_r is the scaling ratio of length in the model to length in prototype, Note that, hereafter, the subscript r represents the scaling ratio. While, the Froude number similitude can be somewhat simplistic, considering more complex scaling law is beyond the scope of this paper. Among the shortcomings of such scaling approach, the sediment particle size distortion in the scaled model can be an important issue [e.g. 48, 49], following Melville and Chiew [50] and Melville and Coleman [5], we can conclude that the effect of the sediment particle size can be considered negligible under the experimental conditions in this study where $D/d_p > 25$. As such, it is assumed that using the river sediments of the prototype in the scaled model does not cause any significant error in our study. Discussions on the effect of sediment size scaling in flume physical models can be found in a number of studies [e.g. 19], but it is beyond the scope of this paper.

The stiffness (K) and the first natural frequency (PNF) of a pier can be simplified using a cantilever beam approach as follows

$$K = \frac{48E \cdot I}{h_p^3} \quad (3)$$

$$PNF = \frac{1}{2\pi} \sqrt{\frac{K}{M}}$$

where E is the elastic modulus, $I = \pi/64 \times (D_{out}^4 - D_{inn}^4)$ is the second moment of area that can be found using the inner and outer diameter (D_{inn} and D_{out} are the inner and outer diameter of the PVC pipe, respectively) for the model pier, h_p is the height of unburied pier between the deck and the soil surface, and M is the mass of the pier. Using these equations and knowing that $M = volume \times density$, we can arrive at the following scale relationships.

$$K_r = E_r \cdot I_r \cdot L_r^{-3} \quad (4)$$

$$(PNF)_r = K_r^{1/2} \cdot M_r^{-1/2}$$

$$I_r = L_r^4 / [1 - (D_{inn}^4 / D_{out}^4)]$$

where γ is the density of the pier. The scaling factors derived based on Froude number similitude are provided in Table 1 along with the magnitude of parameters at both model and prototype scales.

Table 1. Scaling laws and scaling factors with corresponding magnitudes in model and prototype.

Parameter	Scaling factor relationship	Scaling	Magnitude		Unit
			Model	Prototype	
Length (L_r)	L_r	1:50	0.3	15	m
Pier width (D)	$D_r = L_r$	1:50	0.025	1.25	m
Scour depth (d_s)	$d_{s,r} = L_r$	1:50	0.01*	0.5	m
Sediment diameter (d_p)	$d_{p,r} = 1$	1:1	0.78	0.78	mm
Effective sediment density ($\Delta\rho$)	$\Delta\rho_r = 1$	1:1	1.6	1.60	$\frac{g}{cm^3}$
Water velocity (V)	$V_r = L_r^{1/2}$	1:7.071	0.33	0.88	m/s
Time (T)	$T_r = L_r^{1/2}$	1:50	6*	300	hr
Pier elastic modulus (E)	E_r	1:12	2.5	30	MPa
Pier density (γ)	γ_r	1:4.92	0.406^	2	$\frac{g}{cm^3}$
Mass of pier (M)	$M_r = \gamma_r \cdot L_r^3$	1:615,351	0.0598	5206.5	kg
Second moment of area (I)	$\frac{I_r}{L_r^4} = [1 - (D_{inn}^4/D_{out}^4)]^{-1}$	1:12,447,010	9.6E-9	1.2E-1	m^4
Stiffness of bridge pier (K)	$K_r = E_r \cdot I_r \cdot L_r^{-3}$	1:1,195	43	18.1E6	N/m
First natural frequency (PNF)	$PNF_r = E_r^{1/2} \cdot \gamma_r^{-1/2} \cdot L_r^{-3} \cdot I_r^{1/2}$	22.7:1	42.01†	92.56	Hz

* A typical test durations time is used.

^ The density calculated for the hollow cylinder

† PNF calculated for perfect cantilever beam

2.3. Background on FDD and Data Analysis Procedure

The data gathered during experiments are raw acceleration records and need to be adequately processed in order to estimate the modal parameters which can then be related to the measurement of scour depth. The technique employed in this paper is an extension of the classical frequency domain approach often referred to as the basic frequency domain (BFD) technique, or the peak picking technique. The classical approach is based on simple signal processing using a discrete FFT, and uses the fact that well separated modes can be estimated directly from the power spectral density matrix at the peak [51]. The classical techniques, however, can have difficulty detecting the close modes, and, the frequency estimates are limited by the frequency resolution of the spectral density estimate and, in all cases, damping estimation is uncertain or impossible [38].

The so-called Frequency Domain Decomposition (FDD) technique removes all the disadvantages associated with the classical approach, taking advantage of the Singular Value Decomposition (SVD) of the spectral matrix, the spectral matrix is decomposed into a set of auto spectral density functions, each corresponding to a single degree of freedom (SDOF) system. This result is exact in the case where the loading is white noise, the structure is lightly damped and when the mode shapes of close modes are geometrically orthogonal. If these assumptions are not satisfied the decomposition into SDOF systems is approximate, but still the results are significantly more accurate than the results of the classical approach [38].

The FDD method is based on the SVD of the measured PSD matrix of the recorded response, $G_{yy}(f_i)$, at discrete frequencies of $f = f_1, f_2, \dots, f_i$, as shown in Equation 5, 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 each 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 [52].

$$G_{yy}(f) = U(f)[S(f)]U^T(f) \quad (5)$$

The data analysis using the FDD technique explained above, was carried out in MATLAB2019. First, the recorded acceleration data from both accelerometers was imported into MATLAB and then

a pre-processing procedure was used following the principles of Enhanced Frequency Domain Decomposition (EFDD) method [e.g. 53, 54] to filter the acceleration data. The first step in pre-processing is normalisation of all measurement channels (two channels in our experiments) to have zero mean and unit variance. Then, a narrow bandpass filter is applied to data. Following that, based on Welch's method, the PSD and SVD are calculated. In order to remove the harmonic components from the SVD curve, the Kurtosis test was conducted as described in details in the relevant literature [53, 55, 56]. Upon identifying and removing the harmonic components, peaks of SVD are picked, where the frequencies associated with the selected peaks are the natural frequency of the modes (PNFs). This procedure is repeated at 5-minute intervals of the collected acceleration data to enable the assessment of the change in PNFs versus time. It is worth noting that due to the low natural frequencies present in structural health monitoring applications, relatively long periods of data is required to ensure sufficient data points and peaks in the modal analysis, but EFDD provides an advantage over other methods of operational modal analysis (e.g. SSI-COV)

3. Results and Discussion

three experiments were conducted with different burial depths (d_b) of 75 mm, 65 mm, and 60 mm, while all other experimental parameters were the same (see Table 2). The measured maximum scour depth versus time is presented in Figure 4a for these tests. It can be seen that the evolution of maximum scour depth is very similar between the three tests, although it may seem that scour development occurs faster test A with a smaller buried depth. This may be due to the slight differences (smaller than the tolerance of the measurements) between experimental parameters such as water velocity, or may be due to difference in the level of sand compaction, or even due to natural variability in soil characteristics. The cylinder is founded on free standing location and it has not any pile foundation connected to this pier and soil. Meanwhile, the soil near the bridge pier is compacted and soil bed is completely levelled. The general trends in evolution of maximum scour depth are very similar to those found in existing literature [e.g. 19]. An attempt was made to characterise the scour development phases in Figure 4b which present the normalised scour depth versus time with different phases as presented by Hoffmans and Verheij [57].

Table 2. experimental characteristics for the two tests.

Parameter	Test A	Test B	Test C	Unit
Mean water velocity (V)	0.33	0.33	0.33	m/s
Pier diameter (D)	25	25	25	mm
Water height (h_w)	100	100	100	mm
mean particle diameter (d_{50})	0.78	0.78	0.78	mm
Buried depth (d_b)	75	65	60	mm

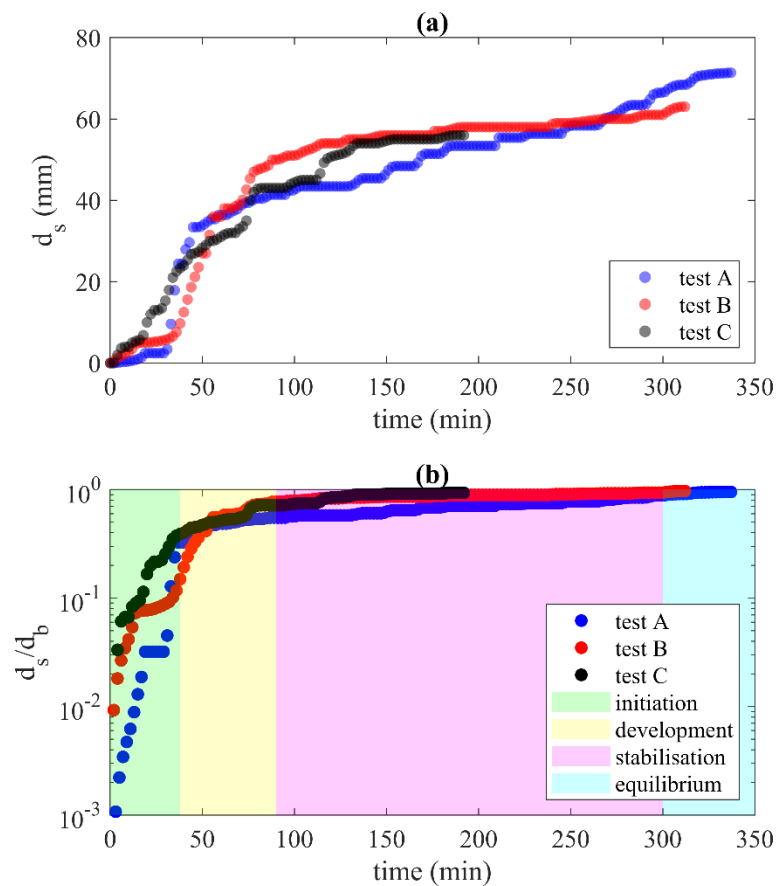


Figure 4. (a) evolution of maximum scour depth with time in both experiments; (b) normalised maximum scour depth versus time with regards to different temporal phases of scour.

In order to show the extent of scouring zone around the pier, the photographs of the zone around the pier before and after scouring is depicted in Figure 5. It can be seen that prior to testing (Figure 5a), the sand bed has a flat morphology as care was taken when preparing the soil to ensure surface has no wrinkle or ups and downs. After scouring (Figure 5b), scour hole is formed at upstream side of the pier which has a diameter nearly 3 times of the pier diameter. On downstream, the sand particles have been deposited, consistent with observation of previous studies as presented in introduction and Figure 1c.

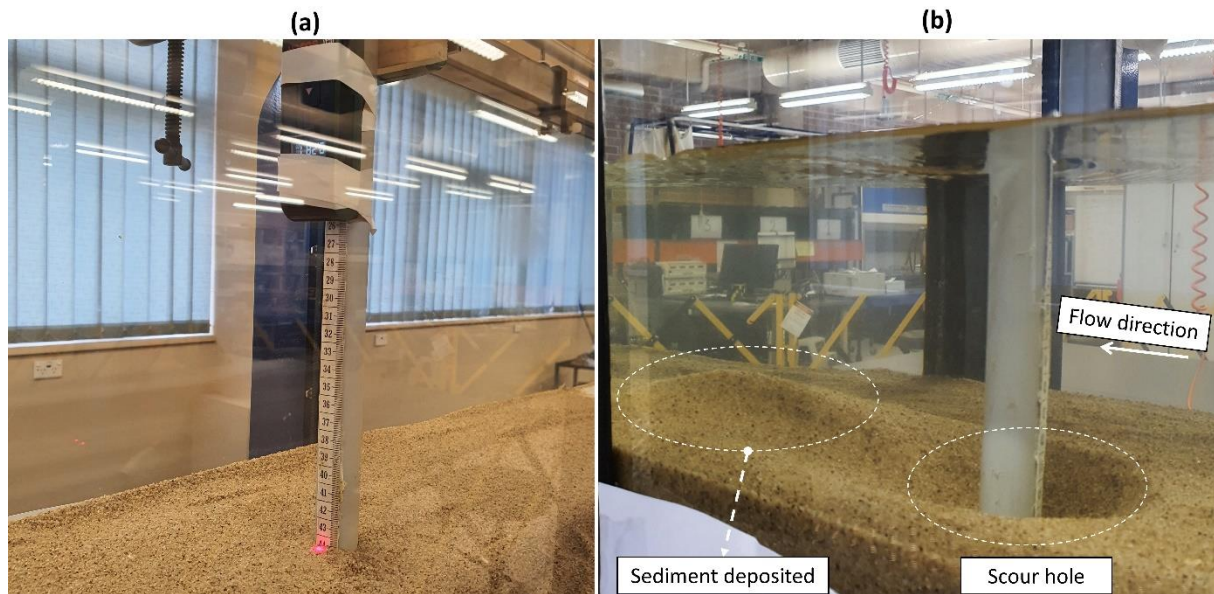


Figure 5. photographs of bridge pier and bed materials: (a) before water flow, (b) after 70 minutes of water flow.

The results of the modal analysis and extracted PNFs in each experiment is also shown in Figure 6 for the first three modes. The right y-axis in these charts also shows the measured maximum scour depth. As explained earlier, the modal analysis using the EFDD techniques was conducted in 5-minute intervals through which the PNFs for the first three modes were extracted which captures the changes in PNFs of the deck-pier-bed structural system as a result of scour hole development. As it can be seen, all three modes in all three experiments show a steep reduction with time following the growth of the scour hole (i.e. increasing maximum scour depth). It also interestingly shows that during the initiation phase of scour hole evolution, the PNFs remain relatively unchanged but it decreases sharply within the development phase of scour hole evolution. As discussed earlier, the reduction in natural frequency is due to change in the stiffness of the structural system which is compromised as a result of scour hole development around the pier. When the maximum scour hole reaches around 50 percent of the buried depth, the PNFs remains nearly constant, which suggests that relationship between the maximum scour depth and PNF is highly nonlinear. However, it should be noted that this latter effect may be due to the constrained boundary condition of the pier and the deck which are fixed to the sides of the hydraulic flume to simulate the effect of bridge abutment. As such, the experiments conducted in this study represent an ideal single pier bridge whose abutments have not affected by scouring, but in reality, the riverbed around the abutment may also undergo scouring which may further compromise the stiffness and hence its stability and the PNFs may continue to decrease beyond the 50 percent observed in these experiments. While the results of this study are generally in agreement with the existing literature that show a reducing trend in PNFs with the increasing maximum scour depth [e.g. 32], the existing literature lacked a very clear trend of the temporal changes in PNFs mainly due to their limitations with their PNF extraction techniques.

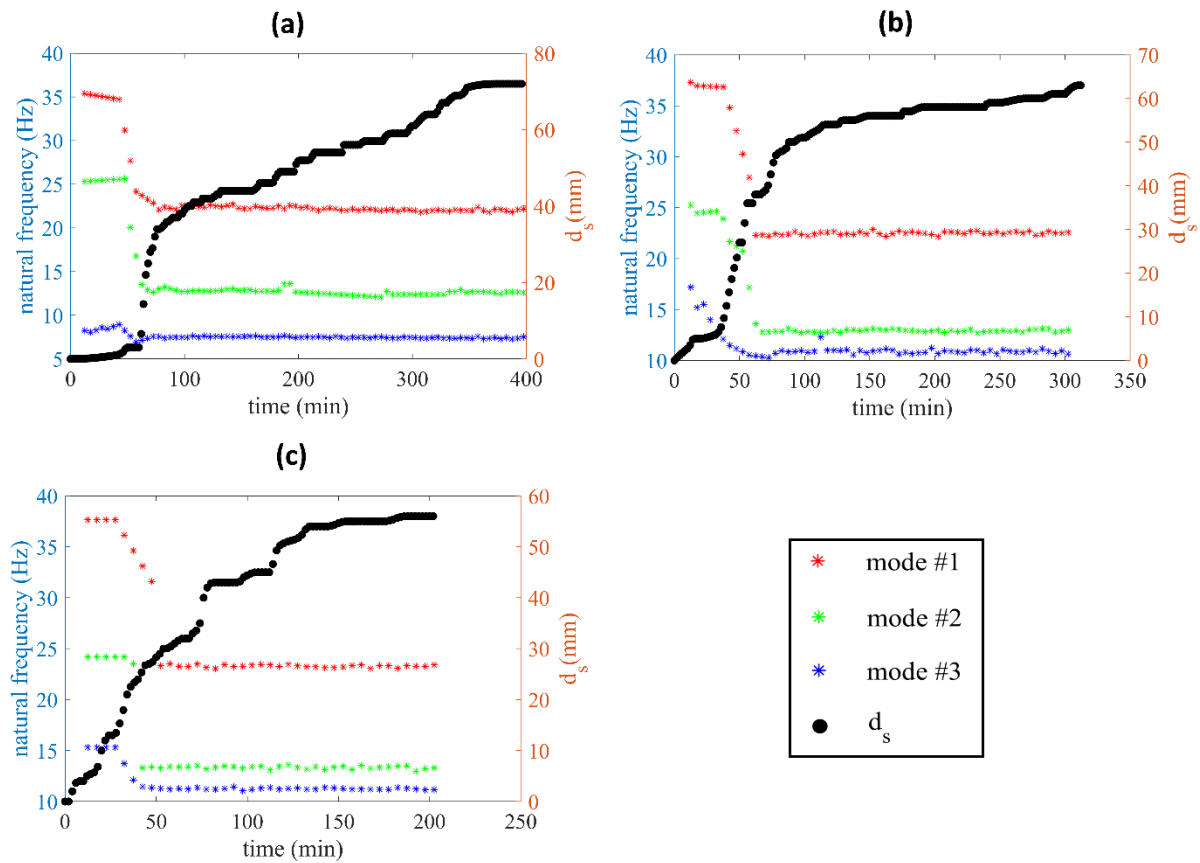


Figure 6. the temporal changes in the first three natural frequency: (a) test A, (b) test B, and (c) test C.

In order to further analyse the relationship between PNFs and the maximum scour depth, the dimensionless reduction of PNFs (δf_n^*) were also presented versus the dimensionless maximum scour depth (the ratio of maximum scour depth to buried depth of the pier, d_s/d_b) in Figure 7. Note that the reduction of PNFs is defined as $\delta f_n^* = (f_n^0 - f_n)/f_n^0$, where f_n^0 is the initial unchanged PNF and f_n is the instantaneous PNF. It can be seen that the second mode of frequency has the largest ultimate reduction in all three experiments, while the third modal frequency has the smallest. Figure 8 shows the average of the change in the first three modes of PNFs for each experiment. This chart can be considered as an attempt to relate the changes in PNFs to maximum scour depth and consequently the stability of a model bridge affected by scouring. Such approach for field application can provide a near real-time monitoring strategy (only 5-minute lag) for firsthand estimation of the scour hole depth around the pier. However, it should be noted that the variability and uncertainties is somewhat more pronounced here in Figure 7 and Figure 8, but the general conclusions drawn from Figure 6 is still valid. This chart can provide a practical guide for estimation and severity of the scour hole development. Further experimental, analytical and/or numerical works are required along with more advanced data analysis techniques to evaluate the impact of scour on the overall stability of the bridge, so that an early-warning threshold can be determined for different types of bridge based on the scour hole growth, but it is evident that for such ideal model bridge, a δf_n^* value of 0.3 can be selected as an early warning threshold that coincides with d_s/d_b value of 0.4-0.5.

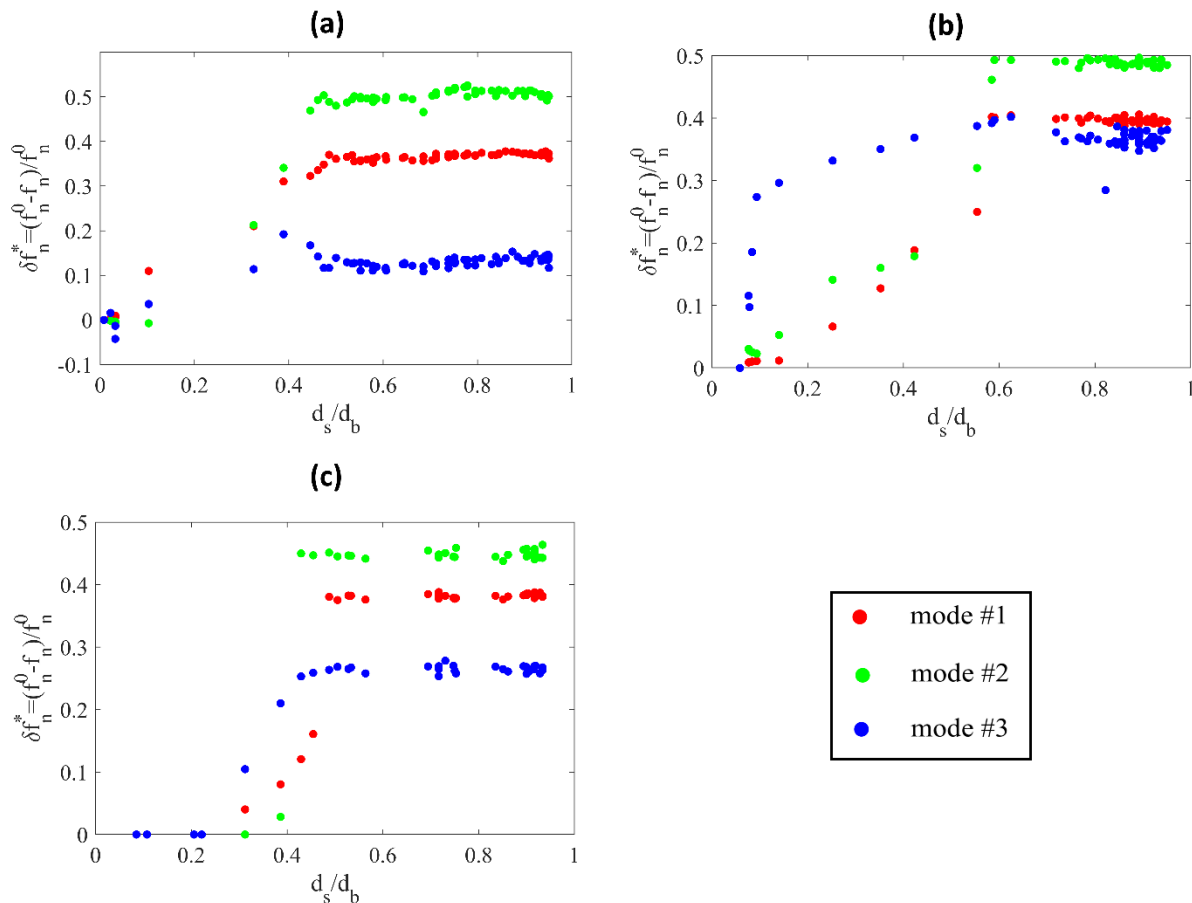


Figure 7. the dimensionless reduction in the first three natural frequency versus dimensionless maximum scour depth: (a) test A, (b) test B and (c) test C.

Another important observation from these figures is that the maximum scour depth increases so fast that the measured PNFs at the 5-minute intervals seems insufficient. However, PNF estimation at smaller time intervals may become unreliable if not impossible by EFDD technique (or any other technique for that matter), mainly because the acceleration data may not be enough for efficient estimation of PSD and SVD. This problem will not be rectified with recording data at a higher frequency as it can introduce additional layers of white noise to the data and it may not increase the data density at the desired frequency range at all. Thus, it is imperative to conduct experiments at lower water velocities where scour hole development takes place at a slower pace, in order to better capture the trend of δf_n^* with respect to scour depth.

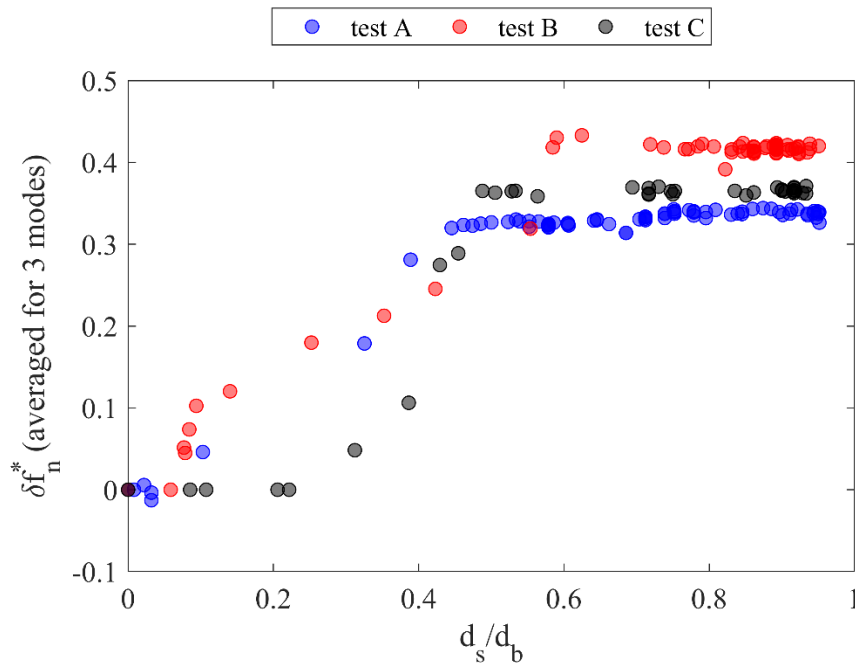


Figure 8. averaged dimensionless reduction of the first three natural frequency versus dimensionless maximum scour depth: (a) test A, (b) test B and (c) test C.

4. Conclusions and Future Developments

This paper presents the results of a series of physical modelling studies on local scour around an ideal bridge pier, where an acceleration-based monitoring strategy has been utilised towards the development of a real-time monitoring technique. The acceleration-based monitoring techniques have been used in structural health monitoring for decades, but for bridge scour monitoring, it has been deemed challenging. This paper provides a novel framework which will serve as a building block for bridge stability monitoring. In this framework, a relatively new modal analysis technique (EFDD) has been employed that allows a more reliable PNF extraction from ambient vibration with short time lag (in order of few minutes). The promising results presented in this study is a giant leap towards the development of a low-cost real-time monitoring technique that can be applied to evaluate the stability of bridge.

It is of utmost importance to discuss the limitations of this study in the context of real-time monitoring of bridge stability. First and foremost, this study is a preliminary investigation of the relationship between the PNFs and maximum scour depth and does not consider some important aspects of bridge stability. Moreover, the bridge model in this study is a single pier bridge whose abutment have not been affected by scouring. Though, in reality the bridge abutment also undergoes scouring and may further reduce the stiffness of the bridge as a structure and consequently the estimated PNFs. Considering uncompromised bridge abutments is commonplace in experimental studies on scour hole evolution around pier in the literature, but when modelling the effect of scouring on bridge stability is important to also study the simultaneous effect of scour on abutment which can give a better picture of the stability of the bridge as a whole influenced by scouring. In addition, having multiple piers in a bridge and considering different arrangements for them can provide a more realistic model for bridge pier scour and the overall stability of the bridge. Moreover, advanced modal analyses are required to identify the mode shapes of the bridge pier under scour influence which will provide better indicators of bridge stability. While, we have only focused on extracted PNFs in this paper, the authors currently working on strategies to extract reliable mode shapes through EFDD technique, which will eventually provide a more comprehensive monitoring capabilities for bridge pier scour. It should be also noted that although the results presented in this paper provides promising results, the application of this algorithm in the real scale can be problematic to some extent. As an example, the scaled model here presented PNFs as high as 38 Hz

but in the prototype scale it corresponds to a PNF of nearly 1.8 Hz and working with such small frequencies can potentially lead to large errors during harmonic removal and PNF extraction. Moreover, the nature of the deck-pier-bed system in a real bridge can potentially affect the monitoring process, where the interaction between these varying and inhomogeneous system can lead to some difficulties in scour development and PNF extraction.

From a hydraulics point of view, the development of scour hole can be affected by the water velocity. Therefore, a more rigorous study of the effect of water velocity on maximum scour depth and hence the extracted PNFs should be an immediate future study as it can reveal a better picture on the relationship between PNF and the scour depth. In this study, we have selected a velocity very close to the critical velocity but selecting lower velocities for future experiments allows a more reliable and complete relationship between PNFs and maximum scour depth. It should also be noted that PNFs may not only be a function of maximum scour depth but also a function of the three dimensional shape of the scour hole, and therefore measurement of the three dimensional shape of the scour hole and its evolution with time at the same temporal resolution as the extracted PNFs can allow establishing a more rigorous relationship between the PNFs and scour hole development.

Another important aspect that has been largely neglected in studies of the scour hole development and its effect on bridge stability (including this study) is the role of soil types, their hydro-mechanical characteristics, and their variability. Given that scour hole develops as a result of water flow pattern around the soil surrounding the pier, it seems intuitive to heavily focus on hydro-mechanical properties of soil to better understand the local scour mechanisms and its ultimate impact on bridge stability. Most of existing experimental studies have used non-cohesive sandy soils, and while some studies attempted to study the role of cohesion of soil on pier scour [58], the role of other soil characteristics (e.g. consolidation, friction angle, cementation) is not fully understood yet. Therefore, it is important for future studies to focus on the effect of soil's natural variability on scour hole development and structural stability of the bridge.

Appendix A. Peak Picking Through EFDD

The acceleration data recorded by the accelerometers are first transformed from time domain into the frequency domain using the cross power spectral density. Then, the first singular value diagram is evaluated for peaks, for which the corresponding frequencies are the natural frequencies (PNFs). However, peak picking using the regular SVD diagram can be problematic as the harmonic components can present some peak that do not represent an actual mode of frequencies. In order to avoid this from happening, the harmonic components need to be removed from the SVD through the methodologies developed by Jacobsen, Andersen [53]. In this methodology, the following steps are taken in order:

- Each measurement channel is normalized to unit variance and zero mean
- For all frequencies between DC and the Nyquist frequency a narrow bandpass filtering of acceleration around the frequency is performed
- The Kurtosis for the filtered signal around the frequency is calculated
- For each frequency, the mean of the Kurtosis is calculated across the measurement channels
- The median of the Kurtosis of all frequencies is calculated. If the signal is purely Gaussian distributed this measure for the mean will theoretically be 0.
- For each frequency, the deviation of the Kurtosis from the median is calculated. If Kurtosis deviates significantly from median of the Kurtosis, then the distribution around the frequency is different than for the majority of the other frequencies. In such a case the frequency can be characterised as an outlier that should not be included in the estimation of the SDOF functions

Figure A-1 depicts the first singular value diagram with and without the harmonic components and the green bands represents the frequency ranges with harmonic components detected. Then, the peak picking algorithm is performed on the SVD whose harmonic components have been removed as illustrated in Figure A-1.

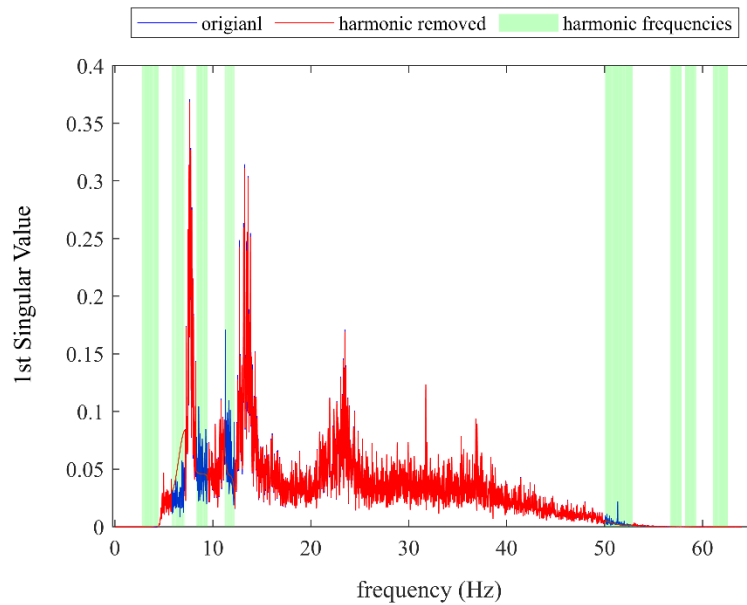


Figure A. removing the harmonic components of the SVD.

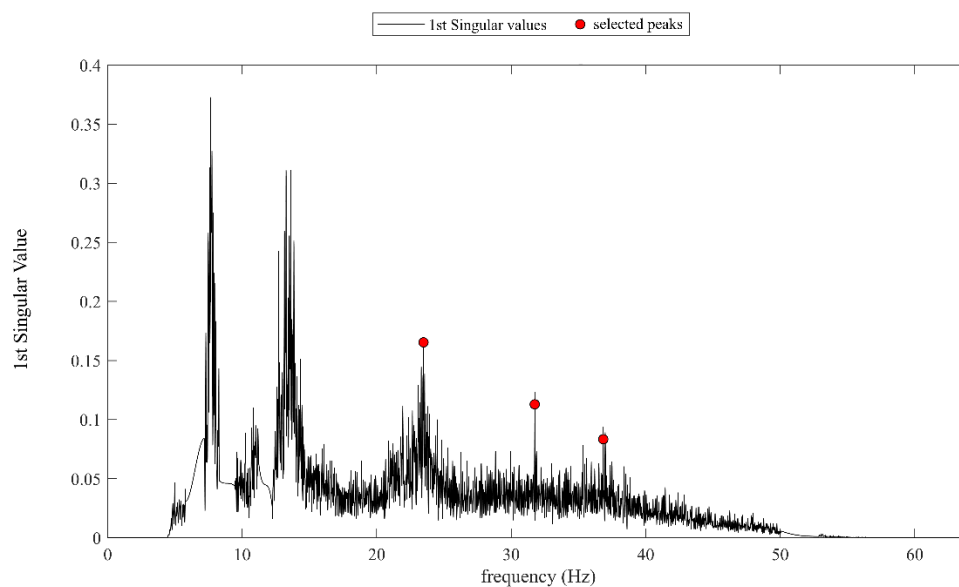


Figure A. a.

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