Published in *Proceedings of the ICE – Bridge Engineering* (In Press) **2024**

Development of a prototype bridge scour sensor exploiting vortex-induced vibrations

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Abstract

The ability to effectively manage the deterioration of a network-wide bridge stock condition from year to year is vital for the effective use of finite resources while maintaining public safety. The leading cause of bridge failures and deterioration globally is bed scour. This paper looks at the development of a novel Fibre Bragg Grating (FBG) Vortex Flow Sensor (VFS) for scour utilising vortex-induced vibration flow effects. These sensors can provide early warnings to bridge managers and allow for a proactive approach to scour management at vulnerable bridges. This paper briefly reviews the current types of scour sensors available before outlining the initial development of the novel VFS setup and associated prototype development. The initial findings of lab trials are presented before outlining the selection process for a masonry arch bridge test site.

Keywords chosen from ICE Publishing list

Bridges; Fibre Bragg Grating, Scour Sensor, Vortex Flow, UN SDG 9, UN SDG 11, UN SDG 12, UN SDG 13

List of abbreviations

FBG	is Fibre Bragg Grating
VFS	is Vortex Flow Sensor
VIV	is Vortex Induced Vibrations
FOC	is Fibre Optic Cable
EMI	is Electromagnetic Interference
NI	is Northern Ireland
DfI	is the Department for Infrastructure

1 Introduction

The issue riverbed scour presents around bridges and other structural assets subject to flowing water is well documented and cited in numerous publications. Although it is expected that most bridges were designed to withstand the expected day to day flows for where they are located at the time of construction, conditions can change over time, and unexpected events can occur. Although flood events tend to be the main driver for scour development at bridges, other factors can come into play such as dredging, changes to storm water outflows, climate change, debris accumulation (Kosič *et al.*, 2023), or even the bridge intrados itself obstructing the flow (Sathurusinghe *et al.*, 2021). Scour has been well established as the leading cause of bridge failure and deterioration in the United States, UK and worldwide (Pizarro *et al.*, 2020; Prendergast *et al.*, 2014) and (Shahriar *et al.*, 2021).

As such, the study of scour and its effects, monitoring requirements, and prevention, is an active area of research and remains a significant issue for asset managers. This paper presents a brief introduction into the types of scour and current monitoring methods, before setting out the development and initial lab trials of a novel scour monitoring device using Fibre Bragg Gratings (FBG) and vortex induced vibrations (VIV).

2 Scour Monitoring

2.1 Types of Scour

The Ciria manual on scour at bridges and other hydraulic structures states structures built in rivers and other channels can be vulnerable to scour around their foundations (Kirby *et al.*, 2015). This manual extensively covers the various types of scour and scour processes but for the purposes of this paper, a high-level outline will be included as background for the sensor development presented later.

Most scour can be classified into three main types: Natural, Contraction and Local (Kirby *et al.*, 2015) which are governed by a myriad of factors including the bed material, flow velocity and

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bed slope geomorphology; while a fourth component of General Scour is considered in the design process (Takano *et al.*, 2021). These factors continuously change in the natural river environment, and despite extensive efforts it is not currently possible to predict the exact extent and severity of scour at a particular structure at a given time or location with 100% certainty. It is therefore necessary to try and manage this uncertainty by a range of means, as presented herein.

2.2 Current Methods

Visual inspections by trained bridge inspectors remains the primary approach taken globally for identifying and assessing suspected scour at a bridge (Pregnolato *et al.*, 2023a) and (Prendergast *et al.*, 2014). The method is highly subjective and normally only conducted following a potential scour event when the floodwater recedes and is deemed safe for inspectors to enter the river. This introduces the potential for infilling masking the true scour extent (Olympio, 2000). Post flood inspections could provide false reassurance to the asset owners and an incomplete picture of the true scour risk, limiting proactive mitigation measures being taken. Risk-based models (Pregnolato *et al.*, 2023b) and remote monitoring have attempted to bridge this gap for asset owners to supplement physical visual inspections.

Research has shown that determining scour conditions affected bridges is fraught with uncertainty and significant challenges. None of the methods currently offer a panacea for the problems faced by asset owners. Factors affecting deployment of scour sensing equipment includes issues with regards to cost, durability, performance, or reliability.

Devices that record maximum scour such as float out devices (Jean-Louis Briaud *et al.*, 2008) and (Prendergast *et al.*, 2014) and magnetic sliding collar devices (NCHRP, 1997) provide limited detail on the progression of scour or subsequent infilling. These devices tend to provide only an indication that scouring has occurred to a discrete depth while not accounting for infilling. They can be compromised by debris preventing them from working as intended thus giving the impression that scouring may not be as severe. This is demonstrated in Figure 1 whereby the float out and magnetic sliding collar devices track the initial scour to bed level 1 shown as (B_1) and (C_1). Should debris lodge under the magnetic sliding collar or above the next float out device, then the bed level could scour further to Level 2 or 3, but the devices would be trapped therefore (B_2) and (C_2) would not be tracked correctly.

Float-Out devices rely on batteries powering a wireless signal to a receiver when activated. It is not typically possible to check the functionality of these devices once installed or if the batteries have depleted, meaning a faulty device could become dislodged and subsequent infilling could hide the event without any triggers being raised.

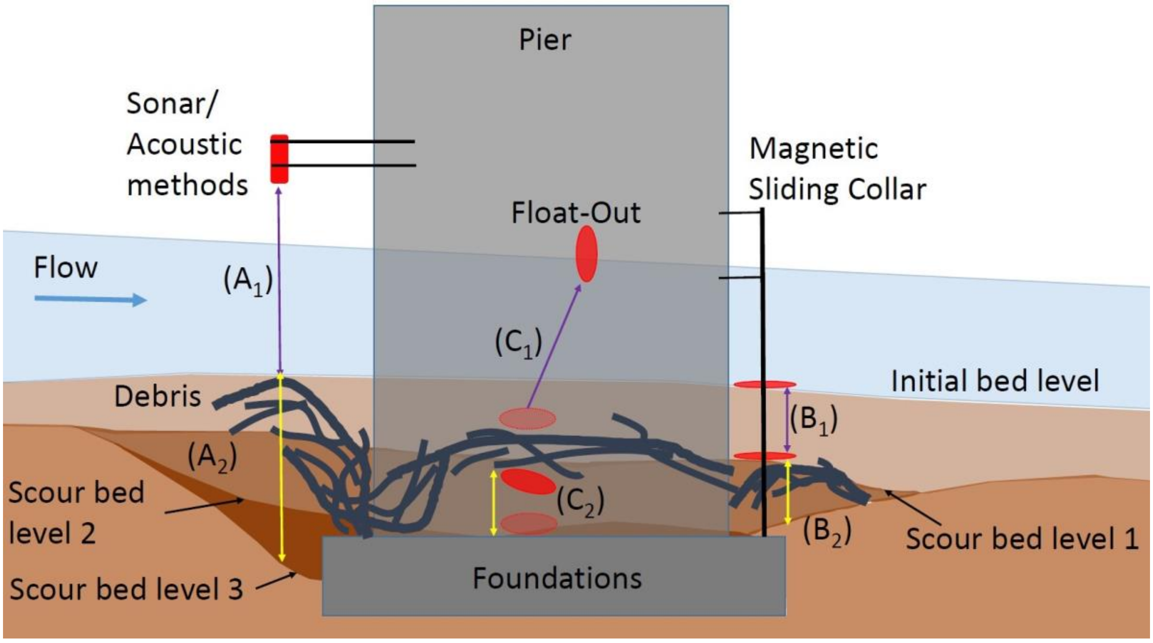

Figure 1 - Magnetic Sliding Collar, tracking the initial stages of scour (B_1), further scouring (B_2) not recorded due to debris. Float-Out device, alerting initial scour (C_1) but debris preventing further alerts (C_2). Acoustic devices (A_1), Debris reducing the depth reading artificially by (A_2).

Devices that record the development of scour such as acoustic devices, radar and other buried sensor arrangements provide more information on the event. Although these present a good way of tracking the development of scour at a location and are relatively easy to install, they can be cost prohibitive and susceptible to water borne debris both from physical impact damage/ vandalism or by giving non-representative measurements to bed level. As seen in Figure 1 should significant debris be in place it is possible that a device could register no notable change in bed level (A_1) despite further scouring occurring (A_2). Some devices are limited to freshwater environments or areas free of metallic debris.

Indirect methods of scour monitoring require a structural assessment of the bridge followed by sensors or vision-based computer methods detecting changes in the structural response (Fitzgerald *et al.*, 2020) ans (Prendergast *et al.*, 2016). This approach requires a greater understanding of the likely structural response of each bridge to scouring. Although this method provides ongoing indications of performance it has the inherent drawback of only providing a trigger that something has changed once damage has started to occur and impact the performance. Examples include installing accelerometers to points of interest on structures and recording the typical response to loading. Should the response change then this could indicate damage to the structure which could be related to scour, or equally to other effects. Vision-based systems relies on cameras recording the structural response to loading and comparing images to see if something changes which could indicate a deteriorating structure.

3 Fiber Bragg Grating (FBG) Sensor Development

3.1 Vortex flow

The principle of vortex flow is based on an object (a bluff body) obstructing flow which results in oscillating vortices forming downstream of the object. When the bluff body of known dimensions is placed into a flow, this generates an alternating pressure in the flow in line with the vortex shedding principal (Cheng *et al.*, 2011) and (Ordonez *et al.*, 2007). This causes vortex induced vibrations (VIV) in which the dominant vibrational frequency is proportional to the flow velocity. Within a pipe of known dimensions, a determination of flow can be obtained from the VIV. This phenomenon has been utilised in the development of accurate flow sensors in the oil and gas industry as well as aeronautical and other applications (Cheng *et al.*, 2011) and in energy harvesting (Cao *et al.*, 2021).

One method of capturing the flow measurement is to attach a flexible fin to the downstream face of the bluff body which moves with the frequency of the vortex shedding. The frequency response of the VIV is captured via a sensor embedded in the fin (Cheng *et al.*, 2011). The research presented in this paper is focused on adapting this technology to capture river flow conditions during scouring events at bridge piers.

3.2 Applications to scour measurement.

To apply a vortex flow approach in the detection of bridge scour, this research proposes a vortex flow sensor which is embedded in the riverbed in close proximity to the bridge pier or scour risk location. When scour occurs this erosion of the riverbed will expose the sensor leading to the occurrence of vortices which induce a vibration response to trigger an alert to the bridge manager. The ability to pick up VIV can be utilised to give a binary ‘Activated’, ‘Inactive’ indicator for scour identification.

The proposed sensor works on the basic principle that the fin element of a vortex flow sensor (VFS) will vibrate when exposed to flowing water, whereas buried VFS fins are not exposed to flowing water and would not vibrate beyond ambient background values. If a fin is buried at a known depth relative to the bridge foundation, then when that fin is buried the bed level must be at least higher than that fin, therefore the bed level is above the foundation level. However, if the fin becomes exposed then the bed level must be at the level of the base of that fin or lower, which could mean the foundations are about to be undermined. As shown in Figure 2, if the VFS has a number of discrete fins along the depth of the bluff body and at known depths relative to the bridge supports, it is possible to indicate the depth of scour at that location based on the captured response for each fin.

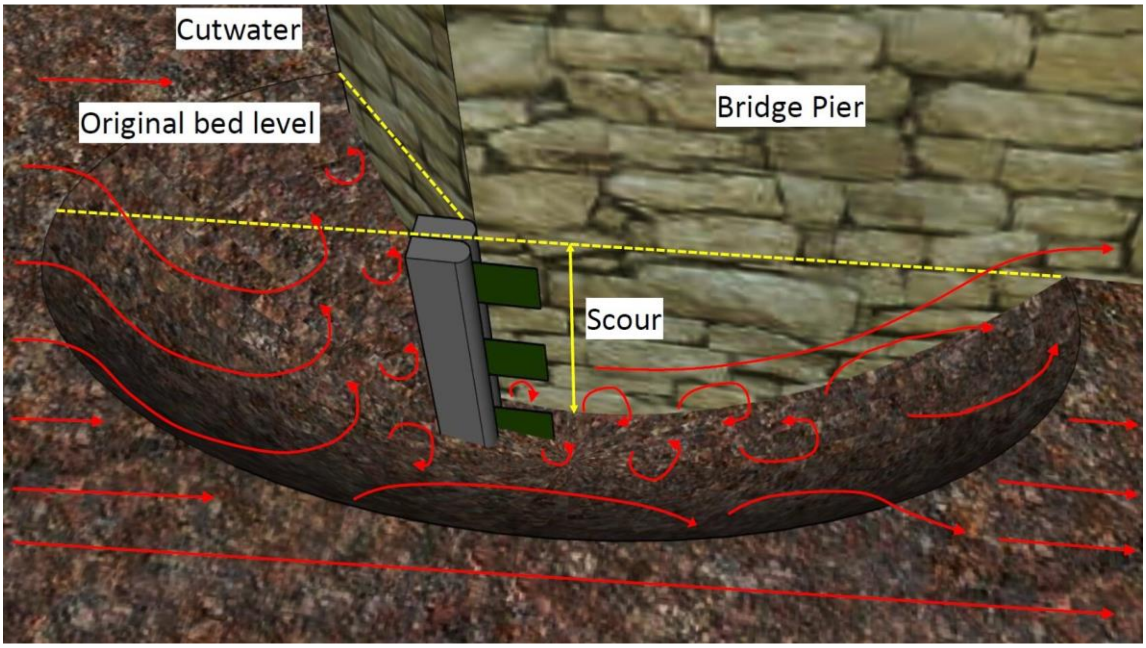

Figure 2 - Proposed VFS arrangement (red arrows indicate indicative flow movement).

The greater number of VFS fins with a smaller spacing will increase the resolution of the tracking of the scour and infill process in real-time.

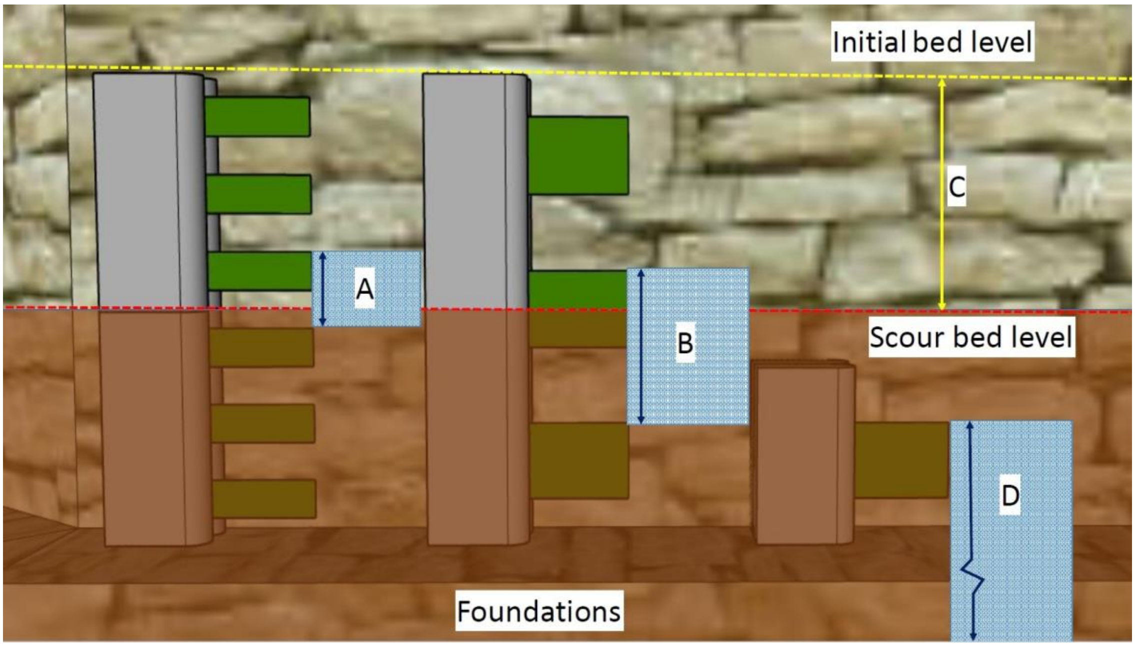

Figure 3 - VFS fin resolution.

As demonstrated by Figure 3, if the number of fins is increased and the fin spacing is reduced, the depth of scour (C) can be narrowed down from the range shown as (B) to (A), which is the distance between the tops of adjacent fins. One fin would enable the determination of scour depth from the top of that fin to an undefined distance below (D). If the sole purpose of this sensor was to give a maximum allowable scour depth before a warning is issued to the asset owner indicating action was required, then only one fin is needed. However multiple fins could be used to aggregate the level of response providing levels of early warning.

This sensor potentially overcomes several of the limitations of many current methods by providing real-time feedback on the scour event including the infilling process, while not being as acutely affected by debris as discussed in section 2.2. It has minimal mechanical parts located within the riverbed environment which can degrade or foul with time and can be readily checked that it is functioning, an aspect that is more difficult with other buried devices. The sensor can operate in both aquatic and marine environments and is unaffected by the proximity of metallic or background noise. It is not as limited to the effective sensing range of methods relying on acoustic or wireless transmissions, so can be installed at depths that would not be appropriate for other methods. Having the known location of the fins relative to the structure gives an accurate reference of depth, whereas other methods could become stuck at a depth or masked by infill, without the inspector knowing the true maximum extent of scour.

The main limitations for this proposed sensor are the need for a stable power supply, the protection of the Fibre optic cable during installation and operation and the equipment costs relative to other methods available. These limitations may be discounted when considering a structure's importance to the network, public safety risk, or the complexity (and costs) of regular underwater inspections.

3.3 FBG fin initial investigations

A rubber flexible fin with an embedded Fibre Optic Cable (FOC) with FBG's was proposed for the initial prototype sensor. The background and principal of FBG sensors is described in detail within (Chan *et al.*, 2006) and (Lydon *et al.*, 2014) , however for the purposes of this paper a very brief summary is included as background. The basic concept is that a known input spectrum of light is transmitted through the FOC. This FOC has FBG's of known spacing that reflect a specified proportion of the input spectrum. When the FOC (at the location of the FBG) lengthens or contracts, this results in a slight shift in the spacing and therefore a change in the reflected spectrum is detected. FBGs are now well established for the measurement of strain, temperature, pressure, and acceleration. FBG's are a good choice for this prototype, since each fin can be instrumented with one single cable returning to the data acquisition point. Furthermore, FBG's are small and lightweight, electrically passive and immune to electromagnetic interference (EMI), a key issue for electrical railways and aquatic locations (Grattan, Basheer, *et al.*, 2009) and (Grattan, Taylor, *et al.*, 2009).

Initial trials utilised a FBG bonded to a 2mm thick rubber fin with a second rubber fin of 1mm layered on top. This encapsulated the FBG to provide a certain level of protection during tests. Flow induced movement would transfer through the rubber to the FBG and register a response. To limit the potential for excessive bending or impact damage to the FOC/FBG it was necessary to establish the minimum required protrusion of the FBGs to pick up movement in the fins while also considering the minimum bend radius of the FOC.

4 Sensor development and testing

4.1 Sensor prototype

The initial prototype sensor consisted of a FBG embedded between two layers of rubber sheet which in turn was encased between two stainless steel hollow sections, (80mm x 40mm x 300mm) with a section of rounded hollow section, (20mm radius) welded to one end. Three rubber fins project 120mm from the square hollow section (100mm beyond the rounded profile) and 50mm wide with 50mm spacings. The FBGs are located within a 20mm projection from the square hollow section as shown in Figure 4. This projection allows for the FBG to effectively track the strains of the bending rubber fin while not projecting too far out that it could become damaged by debris impact which might excessively bend the rubber fin and damage the FBG.

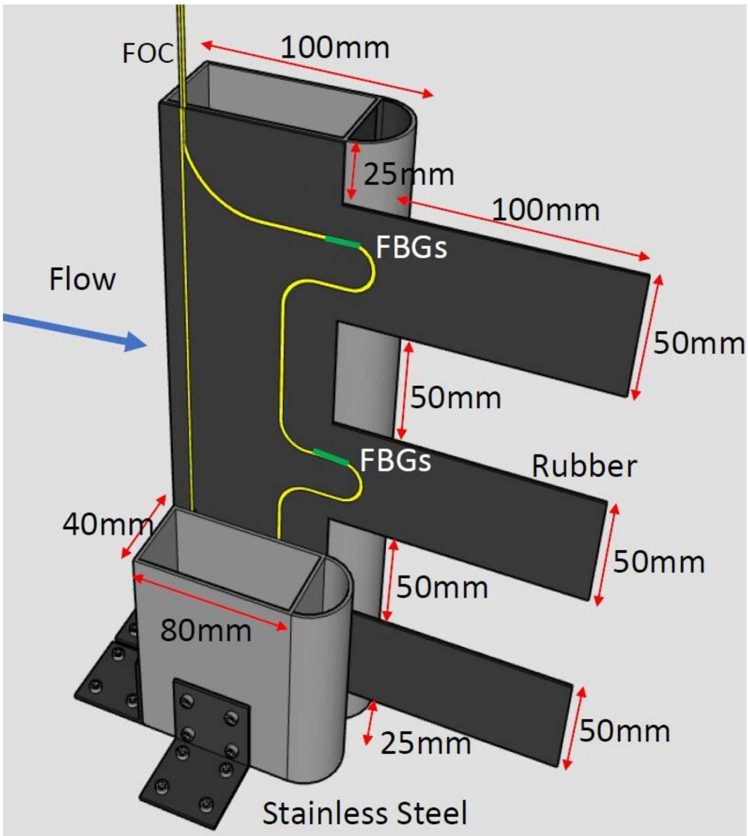

Figure 4 - Prototype dimensions with cutaway to show indicative FBG location embedded between two layers of rubber creating the fins.

4.2 Initial laboratory trial set up

Prior to site installation, initial laboratory trials were undertaken to confirm the capability of the sensor to detect low flow conditions using a flume tank. The flume tank which was utilized for the experimentation was 2200 mm in length, 700 mm in width and 135 mm in height. The shallow dept of the tank meant only the bottom fin was submerged as shown in Figure 5. An Optical sensing interrogator with a sampling rate of 1kHz developed by MICRON OPTICS was used with the FBGs, and the unit was connected to a PC via an ethernet cable. During the data acquisition, the interrogator measures the wavelength of the reflected light produced by the swept wavelength laser and converts it into engineering units such as strain, temperature, displacement, acceleration, or tilt. ENLIGHT Sensing Analysis Software was used to capture and visualise the FBG data during the lab test. The flow rate in the tank was measured using a NORTEK Acoustic Doppler Velocimeter, which is capable of measuring velocities in X, Y and Z axis at a sampling rate range of 0.1 Hz to 25 Hz. CollectV software was used for the configuration and logging of the velocimeter. This software reads the data of the velocity in the three dimensions from the velocimeter and plots the velocities in each direction independently at a given scanning rate.

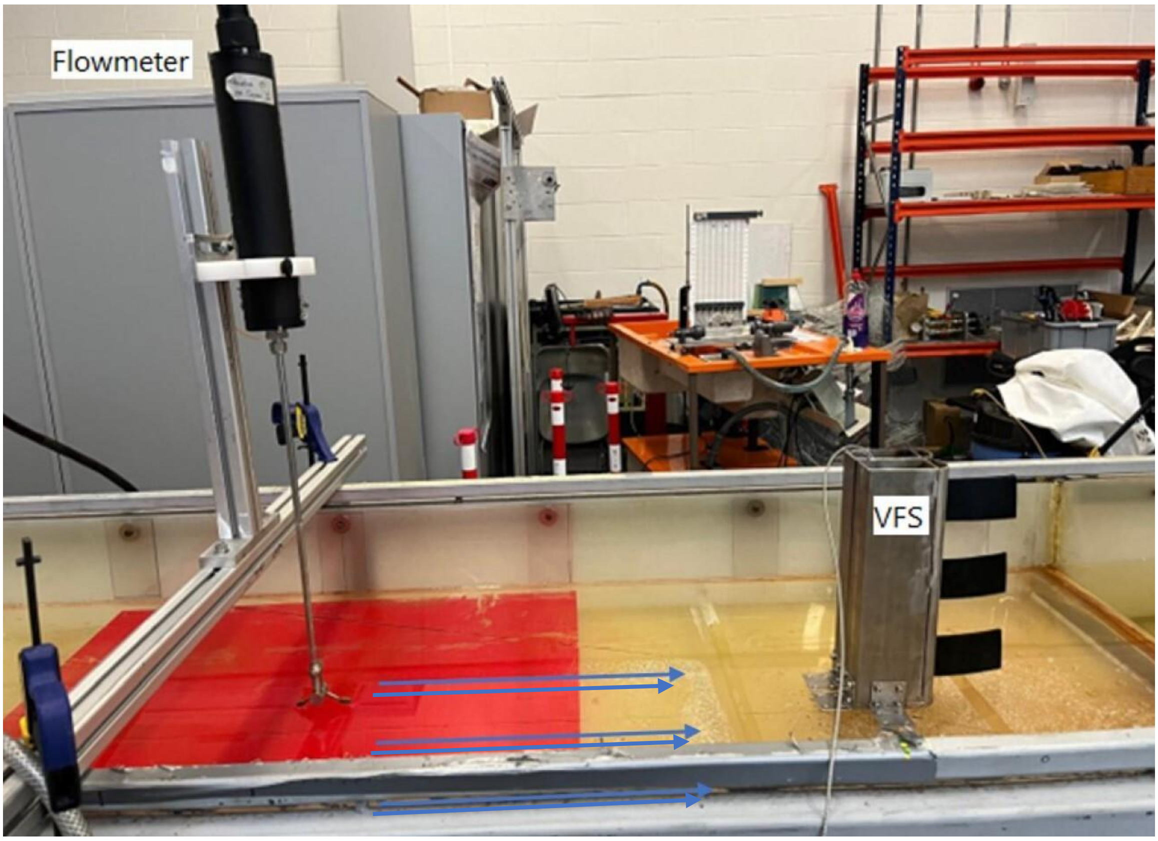

Figure 5 - VFS in flume during lab trails of bottom fin.

4.3 Data acquisition and synchronisation

Both the velocimeter and VFS were set up and configured using the associated software for each sensor and both instruments were oriented perpendicular to the flow of the water as shown in Figure 5. The external values required to configure the velocimeter were the water temperature, which was 18 ℃; water salinity at 0.1 ppt; and the required sampling rate at 1 Hz. The VFS data was collected at a sampling rate of 500Hz. It is acknowledged that this scanning rate would result in a very large data set if implemented in the field and therefore would not be suitable for long term monitoring. However, this scanning rate was selected to enable potential opportunities for future post processing techniques, such as Fast Fourier Transforms, to be applied to the data to correlate the fin response to a flow rate without an independent velocimeter. Two independent PCs were required to simultaneously capture data from each sensor. The data was synchronised using a simple time delay method, the VFS was triggered first and after a period of ten seconds the data logger of the velocimeter was triggered. By matching up the data collected from the velocimeter to the tenth second of the scour sensor data, the link was made for the data to be analysed effectively. To combine the data captured from both sensors, the variation in scanning rate was addressed by the method interpolation between measurement points of the velocity data.

To simulate a no flow Inactive condition, the strain responses of the bottom fin was collected prior to water flowing passed it flowing. This data is presented in Figure 6, where the no scour amplitude range 0 to 5 microstrain can be identified, representing the background noise.

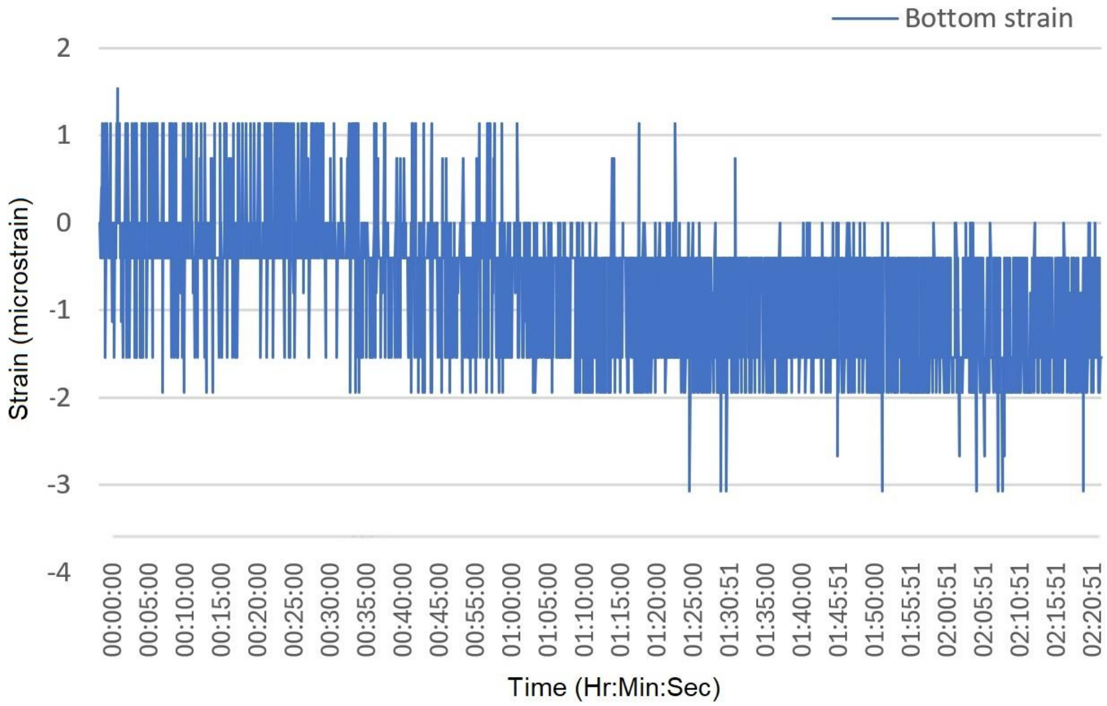

Figure 6 - Strain response of bottom fin of VFS in no flow conditions.

Once the flume was filled with water, Figure 7 presents data showing a high variation in flow rate within a short time span. This variation in velocity was assumed to be noise generated by the flume tank. To get a better understanding of the velocity, a linear trend line was drawn which provided a more stable velocity reading.

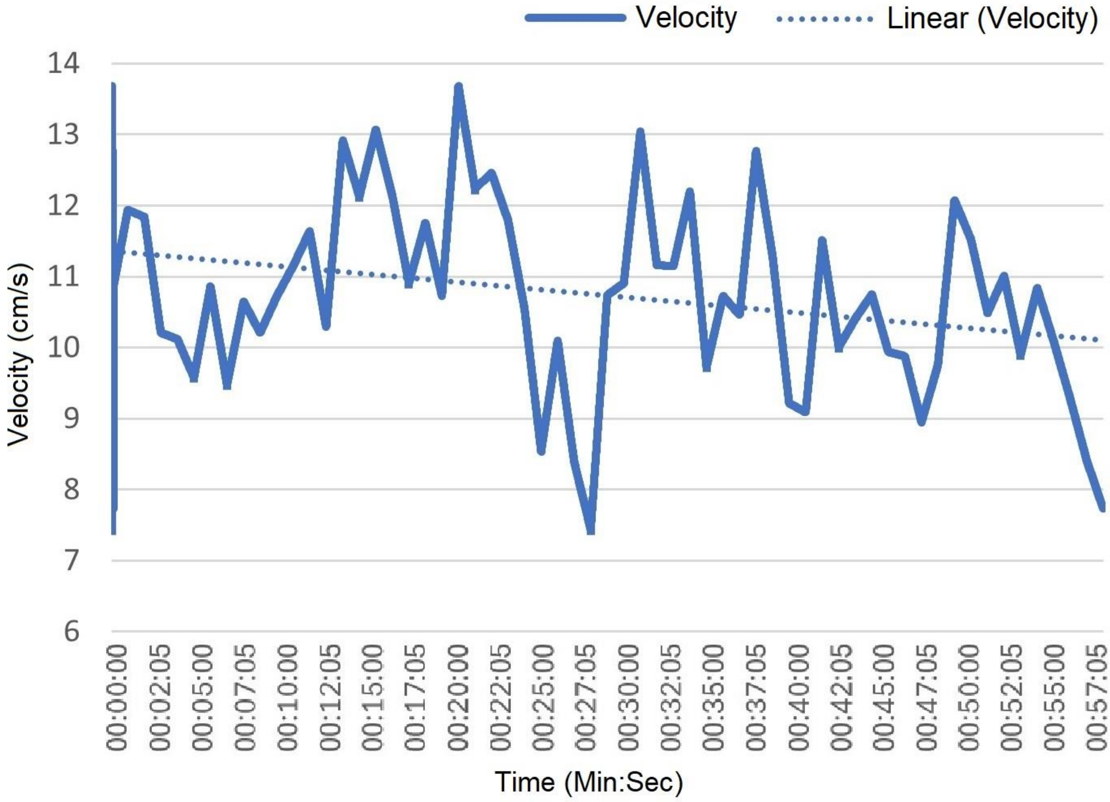

Figure 7 - Velocity vs Time (including linear trendline).

4.4 Results and discussion

The combined result from both sensors is presented in Figure 8, which shows there is no obvious visual relationship between the strain and the velocity readings.

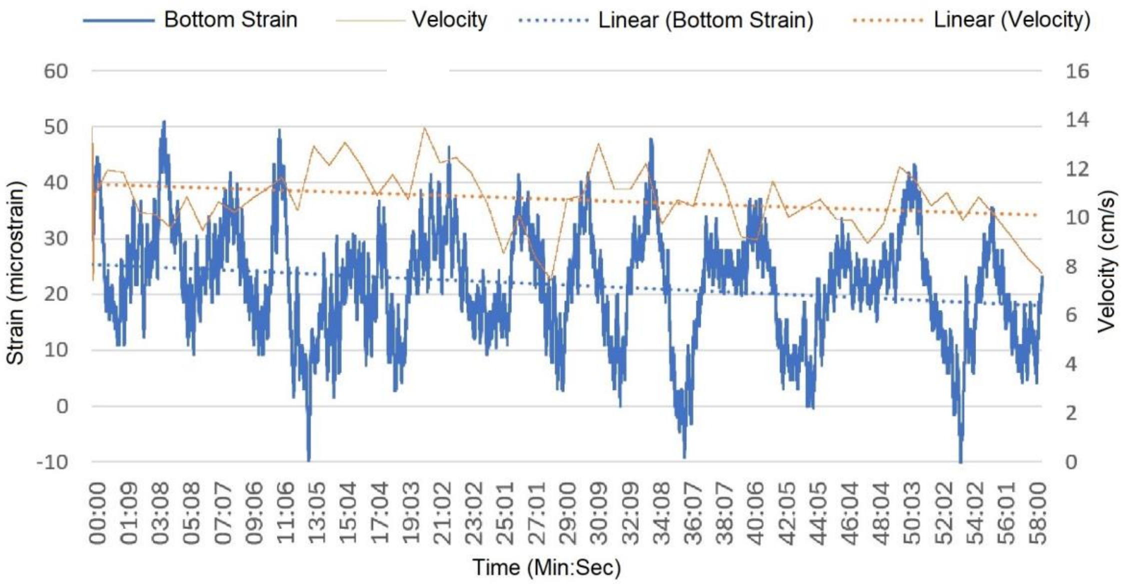

Figure 8 - Strain and Velocity vs Time

However, by analysing the linear trendline of velocity and strain, a clear relationship of the strain amplitude can be visualised. As the velocity of the trendline reduces by 13.56%, the peaks and troughs of the strain readings reduce by 23.91%. The graph shows that the exposure of the fin in low flow conditions can be identified by an increase in magnitude of oscillations in the strain response; in this case the amplitude range is between strain 10 and 40 micro strain. This initial lab trial provided confidence to explore the development of a full-scale field test. The site selection criteria for this test is presented in the following section. Future testing and analysis need to be conducted to get a better understanding of the relationship between strain amplitude and velocity.

5 Bridge site trial

In Northern Ireland (NI), the Department for Infrastructure (DfI) encompasses the role of local Roads Authority and controls and maintains approximately 6000 bridges across the whole of NI (Stevens *et al.*, 2020). These bridges are subject to regular inspections in accordance with CS450 (National Highways, 2021), to assess the overall condition of the structures before identifying any maintenance needs.

Over 53% are classified as masonry arch (Campbell *et al.*, 2020)., but there are significantly more highway structures that DfI are responsible for that are not routinely inspected or maintained as they do not fall within the definition as set out in CS450. A reactive response approach is used for these structures.

A review of the bridge files held by DfI indicates that the majority have limited construction information on the structure including any indication of the foundation depth, type (spread, piled or other) nor the geotechnical properties for what the bridges are founded on (bedrock, clay, sand, gravel, or other).

This lack of detail leads to a conservative approach by DfI bridge inspectors in relation to scour. Potential scour occurrence results in the structure being flagged and its maintenance priority considered predominantly based on engineering judgement.

5.1 Test site

Having established during the initial laboratory trails presented above that the basic concept of the VFS works, the next stage was to set up a longer-term site trial at a bridge.

A test site with a known history of scour was selected in Dromore, Northern Ireland, see Figure 9. This site was both downstream and upstream of river gauging stations, located in a town centre with pedestrian footpath access to the downstream face. Gauging station data would allow the opportunity to refer to real time river flow data at those locations should it be needed. The Upstream face had no access for pedestrians and had an element of cover which would provide a level of protection from vandalism. The bridge spans the River Lagan and the water depth is typically 500-900mm deep but varies during periods of heavy rain or drought. This allows for ready and safe access to install and monitor the sensor during the trial without the need for temporary works and de-watering.

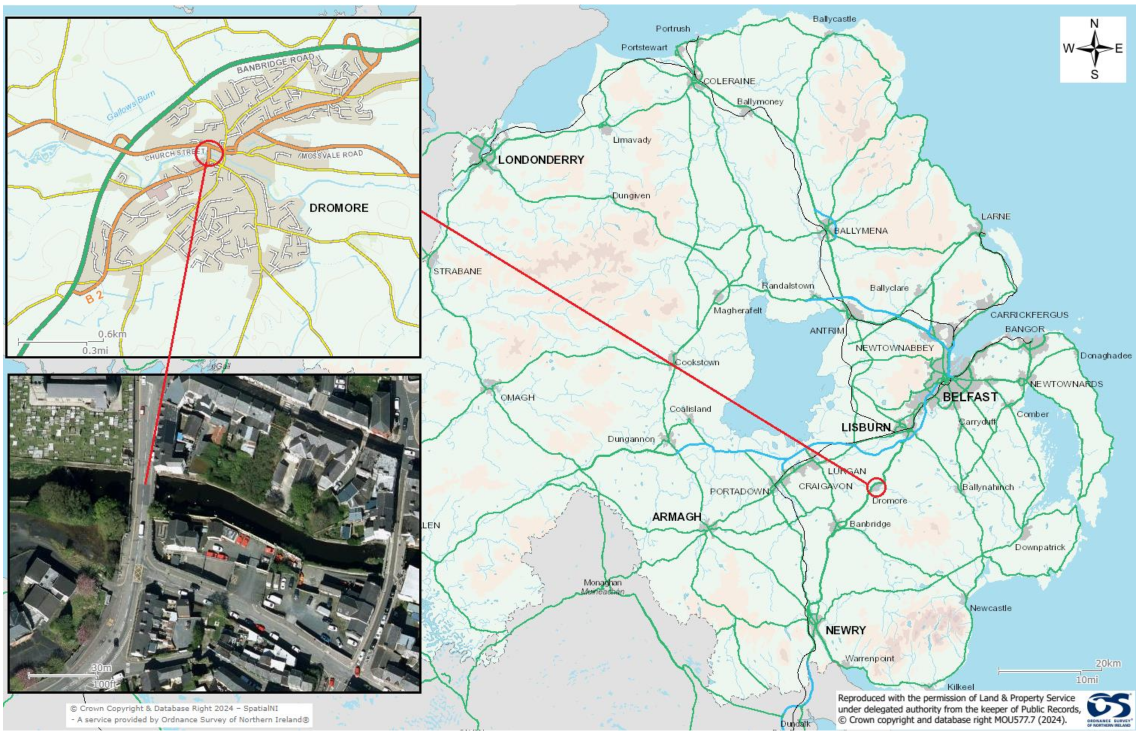

Figure 9 - Location of Regent bridge, Dromore, Northern Ireland

Regent bridge is a three-span masonry arch structure built in the early 19th Century with a cumulative span of 21.4m and a deck width of 11m, see Figure 10. The bridge is a listed structure which means that it is subject to certain protections due to its historic heritage or cultural value. Although the type of bridge structure does not have a direct bearing on the ability of the VFS to detect scour, having established that over 53% of the NI bridge stock are masonry arches, this type was preferred.

Figure 10 - Regent Bridge, Dromore

The sensor was installed at Regent Bridge during a period of dry weather aiding the water levels for installation. The sensor was placed within an existing scour hole adjacent to an upstream cutwater and material from the riverbed was used to infill around the sensor. During this process, the sensor traces were observed and showed that as the fins were buried the data traces would flatten until all three fins were buried. Unfortunately, the data was not recorded during this process as the action of infilling was a very artificial process of placing material around the sensor and compacting it. Therefore, the readings would have been affected by manual agitation of the fin as opposed to solely the effects of river flow induced vibrations.

6 Future research potential

6.1 Future work

The sensor was installed following an extended period of dry weather which ensured low water levels that aided the installation of the sensor. Since installation, the weather has remained predominantly dry and the river levels remain low. Visual inspection of the area surrounding the sensor from photographs taken during installation indicate little movement to the materials in that area, as such it is not expected that any scour has likely occurred during the time of drafting this paper. Although this site trial has evidence of scour around the upstream cutwaters as well as a recorded history of scour from its inspection record, it is not possible to guarantee that the sensor will experience scour in any defined time period. Further laboratory trials will be undertaken to optimise the sensor design and inform on the development of future prototypes. An optimisation of the bluff body and fin arrangement will need to be undertaken akin to the work presented in Mehdipour et al. (2022) although this focussed on energy harvesting potential. A variation to this approach must take cognisance to practical application and durability in a natural river environment. The authors are currently discussing additional field trials on a bridge structure within the UK rail network.

Another area of development includes investigating the effects of debris on the effectiveness of the fins. Although when the fins are exposed this sends a signal and is recorded, the effects of subsequent infilling or debris accumulation around the fins will need to be thoroughly investigated.

7 Conclusions

The issue of scour at bridge structures is a complex but important area of study. This paper has presented the initial work into the development and preliminary testing of a novel real-time scour monitoring sensor using FBG technology. Initial lab trails have shown the concept of rubber fins embedded with FBGs has potential applications in this area. A prototype has been installed on site and data is being collected, which will be analysed in future work. Further work is needed to refine the prototype sensor and deploy to other bridge sites for a prolonged period. This will determine the deployment and running costs of such a sensor setup.

8 Practical Relevance and Potential Application

This research has presented the development of a novel scour sensor which can provide an early warning of damaging effects of a scouring event as it occurs. As such, it provides an opportunity to intervene before subsequent defects present themselves at a significant level that can cause severe damage or even risk to the public. The most cost-efficient intervention point needs to be determined for these bridges and the decision made whether it is worthwhile proactively monitoring and repairing susceptible structures before they reach a point of needing more extensive repairs or a more reactive approach is warranted.

Currently the prototype system requires a 240V wired power supply which for the field trails has been obtained from a connection to an adjacent street lighting column. Work needs to be undertaken to refine the sensor to determine if the concept could be readily deployed to more rural areas with limited access to a wired power source. This may require exploring alternative power sources such as a long-term battery and solar panel. It will also require looking at how best to house the datalogging and interrogator equipment in a waterproof cabinet.

It is the intention of the authors to determine trigger values and to connect the signal outputs from the fins to automatically send a message to a server or bridge manager to warn them that a fin or fins have been exposed and requires action.

Acknowledgements

The authors would like to thank the Department for Infrastructure (DfI) for complete access to all the bridge data, technical and financial support and allowing the findings in this paper to be published. The financial support of the Royal Academy of Engineering under the research fellowship program is also gratefully acknowledged.

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