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Preliminary results of a fiber optic scour sensor (FOSS) for bridges

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ABSTRACT

Bridges are a vital part of the infrastructure that shapes our society. The management of these assets against ever increasing climatic changes is providing unprecedented challenges for bridge asset owners worldwide. The effects of more frequent and severe rainfall flood events in the UK have exacerbated concerns around the management of bridge scour events. This research presents the development and field deployment of a Fiber Optic Scour Sensor (FOSS), designed to remotely monitor scour and infilling in real-time. This sensor consists of three sensing elements (fins) buried at different depths. As scouring occurs, the fins are exposed and free to move and register a response. Following the flood event, as the scour hole begins to infill, these fins are buried, and this process can be picked up on the data trace. A prototype FOSS was installed at Regent bridge in Northern Ireland; a site selected for its accessibility and suitability for monitoring. This paper outlines the installation, and the initial findings, following two storms in October 2023, demonstrating the sensor's potential for real-time scour detection in operational environments.

1. Introduction

Bridges are a vital part of everyday infrastructure systems that the public can often overlook. Aside from the landmark structures, these everyday critical structures come into focus when events cause their closure for repairs or replacement. Bridge asset owners have a responsibility to manage all these structures to ensure safe operation with minimal disturbance to the public.

Bridge owners face a range of challenges when planning the effective management of their assets. Many masonry bridges across the globe are over 100 years old and exceed the design life specified in the Eurocode or British Standards of 100 or 120 years [1]. In Northern Ireland (NI), many of the bridges in operation exceed this age range and, in some cases, are much older. These structures rarely have detailed as-built construction drawings, nor were they constructed with an appreciation of the future loading they would experience with heavier and more frequent motorized traffic loading [2]. Furthermore, climate change and its impact are causing an acceleration of the deterioration of certain assets [3]. Projections of "hotter, drier summers and warmer, wetter winters" are likely to

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result in more frequent extreme precipitation events [4]. These events not only increase the frequency but also enhance the magnitude of flood events at critical structures [5,6]. As a result, these events have a direct influence on increasing the potential scouring of bridge supports adjacent to or within the watercourse. These socio-technological and climatic changes are likely far beyond the original parameters and intended serviceability initially considered by the bridge designers.

It is widely accepted that a leading cause of bridge failure worldwide is either caused by or at least in part due to scouring [7]. Scouring is defined as 'the removal of material from the bed and banks of a channel and from around structure foundations by the action of water' [7]. Detecting a scouring event at known areas of concern during or prior to a flood event would help to manage consequences in a more proactive manner. For example, an early-warning system could provide alerts to bridge managers, while identifying sites that need urgent inspections or corrective interventions. These interventions could be as simple as removing trapped debris at the structure, so the flow is not constrained, installing protective ballast (rip-rap) to protect the foundations, or closing a potentially vulnerable bridge to traffic.

In recent years, significant efforts have been made to develop scour monitoring sensors and manage the risk associated with scouring at bridge piers [8–14]. These monitoring devices are broadly categorized into two types based on the nature of the measured record: direct and indirect scour devices [15]. Direct sensor measures the removal of soil at the foundation level. Examples include single-use float devices, buried or driven rods, electrical conductivity devices, pulse or radar sensors, and dielectric probes, etc. [15]. These sensors present both strengths and limitations. For instance, float devices, though mechanically simple, can only record the maximum scour depth and cannot provide real-time, continuous scour data [9]. Driven rods, based on the basic gravity concept, move downward as scour progresses but are only effective near the pier and are unable to capture the infilling process [16]. Electrical conductivity devices measure scour depth via changes in conductivity at the water-soil interface but are difficult to install, environmentally sensitive, and require regular maintenance [17]. Pulse or radar devices, based on electromagnetic pulses, record real-time scour but are costly, susceptible to debris giving false readings and time-consuming to install [18]. Dielectric probes work on the dielectric properties of water and sediment, offer continuous and highly accurate real-time data, but are sensitive to environmental factors, expensive, and require maintenance [19]. Fibre Bragg Grating (FBG) sensors as part of optic fiber sensing methods can effectively detect strain and temperature changes associated with scour-induced structural shifts in harsh environments without being susceptible to electromagnetic interference [20].

In contrast, indirect measurement devices assess scour by tracking changes in the structure's movement. Examples include tiltmeters, accelerometers, GPS, satellite imaging, etc. [15]. Like direct measurement devices, these sensors also offer specific advantages and disadvantages. Tiltmeters measure the relative rotation of structural elements, with limitations including inability to record direct scour depth, limited sensitivity to small scour, being a reactive approach to scour [21]. Accelerometers record changes in the structural response caused by changes in stiffness as scour progresses, but they are sensitive to noise from nearby machinery and require careful calibration [21]. GPS and satellite imaging offer precise location data and wide-area visual insights, but they are affected by factors like cloud cover, GPS signal interference, and high costs, requiring complex data processing for accurate interpretation [22].

The goal of these sensors is to identify scour or its impact on a structure and to ultimately provide information for decision-making. Although there are methods that claim to track scour and infilling in real-time, these are subject to limitations as mentioned in the above literature. These limitations can lead to false readings as to the true extent of the scour or provide false assurance that scouring has not taken place [9,20]. There remains a clear need to develop a robust real time scour sensor that is less vulnerable to inaccuracies in depth measurements, quickly responds to changes in the scour level and can be used by bridge managers to respond proactively to scour events, making it an ideal sensor for future scour monitoring applications [23].

Hence, this study seeks to address major limitations of earlier developed sensor devices, namely their inability to reliably record both the scouring and infill process in real time whilst in a practical real world test site subject to real world flood conditions. A new FBG based Fibre Optic sensor, named FOSS (Fiber Optic Scour Sensor), aims to fill these gaps. As part of this study, FOSS was deployed and tested on a masonry arch bridge in NI, as a pilot.

The developed FOSS sensor has the capability to detect both removal and refilling of riverbed material, which many traditional sensors cannot capture. FOSS is placed to a known depth fixed to the bridge support meaning it is less susceptible to giving false readings of scour depth. FOSS is not affected by the salinity, quality or clarity of the water and it also offers quick and efficient installation on site as it does not require calibration to determine material properties of the bed material surrounding it. Furthermore, fibre optic sensors based on FBG technology provide good reliability and robustness compared to traditional electrical sensors, especially in challenging environments such as in fast flowing waters with suspended sediments. The passive operation, long-term stability, and ability to be multiplexed along a single fibre makes the FOSS sensor very suited for continuous, real-time monitoring in submerged and remote locations where electrical sensors often fail.

The paper is organized as follows. Section 2 presents the development of the sensor, covering an overview of the sensor, site selection, deployment, setup, and result monitoring. Section 3 will then present the initial data collected during deployment, highlighting its effectiveness in detecting scour during a flood event. Section 4 provides a discussion on the challenges encountered during sensor deployment and benefits that the sensor offered. Finally, Section 5 concludes the paper, summarizing the key results obtained from the sensor and potential for its future scope.

2. Sensor development

Development of the FOSS sensor was initiated in 2021 with a prototype version initially tested in a laboratory in 2022. This paper details FOSS deployment and use at a real case study and refers to several distinct phases in this trial, outlined in Table 1, after successful lab trials [24].

2.1. FOSS overview

The prototype consists of a fibre optic cable (FOC) with three FBG encapsulated between two layers of thin rubber creating three separate 50 mm by 120 mm exposed sensing fins, (Fig. 1).

The sensor assembly comprises of two 200 mm tall stainless steel rectangular hollow sections (40 mm × 80 mm), with fins spaced at 50 mm intervals along the length. Two 40 mm semi-circular hollow sections are welded to the trailing edge to provide protection to the encapsulated FOC, while the leading edge of the rectangular hollow sections act as the bluff body to generate vortices in the passing water flow when exposed, (Fig. 1c and d).

The prototype operates on the basic principle that, when buried, the fins are not exposed to flowing water and do not generate a variable signal in the sensor traces. Once the bed material scours and is removed from around the FOSS, these fins are exposed to flowing water, allowing them to move and generate a measurable response. The three fins are at different depths, so it is possible to track the depth of scouring relative to the sensor installation location (Fig. 1). Once material begins to infill again following the scouring, these fins are reburied, cease movement, and this transition is captured in the data traces. Thus, the FOSS provides a real-time record of both the scour and in filling process, as detailed in the authors' previous publication [24].

2.2. Test site selection

The Department for Infrastructure (DfI) maintains a bridge database of all NI road bridges. This database records a range of information which includes but is not limited to the name, location grid reference, construction details, function (bridge over river), construction date, span details, parapet construction, current and previous bridge inspections. Moreover, DfI holds digital records of river levels and flow from approximately 130 gauging stations located around NI. These datasets were used to select an ideal site for deploying FOSS.

The objective was to identify a suitable testing site, under DfI ownership, with a likelihood to experience scour during the test phase. Fig. 2 shows a summary of the site selection process.

Masonry arch bridges account for approximately 53 % of the total bridge stock in NI [25] and represent the most frequently scour impacted structures in DfI making them a key group to consider. Multi-span masonry arch bridges were then considered, as this type would infer potential piers in the water. Piers within the river are more susceptible to catching woody debris which can cause scour [26], thus improving the chances that a test site would experience scour during the testing phase.

Using data stored within the DfI bridge database, the criteria (outlined in Fig. 2) were then plotted onto Geographic Information System Map Layers. Overlaying these layers on a map enabled the identification of clusters of scour-affected bridges on rivers with gauging stations nearby. Once the prospective test sites were identified, a detailed review of the inspection records was conducted to check on the extent and location of scour and whether any maintenance work had been undertaken or was planned for the next calendar year.

Site visits identified any access constraints and determined the suitability of the sites for instrumentation. Several sites were excluded due to the presence of scour mitigation features such as, aprons, stone pitched floors, exposed bedrock channel beds or concrete inverts which were not in the bridge records. Any bridge site with these features adjacent to the cutwaters was removed from the selection process, since they may impair the sensor's deployment and reduce the likelihood for scour occurring and being recorded during the data acquisition.

The accessibility of the site was verified for both installation and regular inspection, plus the presence of a viable power source. The selection criteria also consider other factors such as the potential for vandalism and the suitability of the riverbed material, in terms of likelihood to experience scour and for the ease of installation. For the purposes of this trial, factors were selected to assist with the ease of installation and to increase the likelihood of a scour event occurring during the sensor's deployment and data acquisition.

FOSS could be adaptable and deployed to any location, at any depth of water (salt or fresh water), where scour is suspected or anticipated to occur given the appropriate safe method of installation can be implemented.

The selection process identified, Regents Bridge in Dromore County Down, NI, as the most suitable test site.

2.3. Test site description

Regents Bridge is a three-span masonry arch bridge built in the early 19th century, with a cumulative total span of 21.4 m and deck

Table 1
Project key events.

Event	Dates	Commentary
Sensor development and laboratory trails	2012–2022	Flume tank and limited river testing.
Site installation	12th February 2023	Data recording started and checked periodically
Implementation Phase	12th February–18th October 2023	Sensor installed on site but data not recoverable.
Computer replacement	18th October 2023	Data was lost up to this date due to a corrupt computer hard drive.
Data acquisition Phase	18th – 31st October 2023	Date collected and presented in this paper.
Sensor recovery Phase	31st October 2023 – 18th October 2024	Sensor left in situ to test its physical robustness against real world conditions.

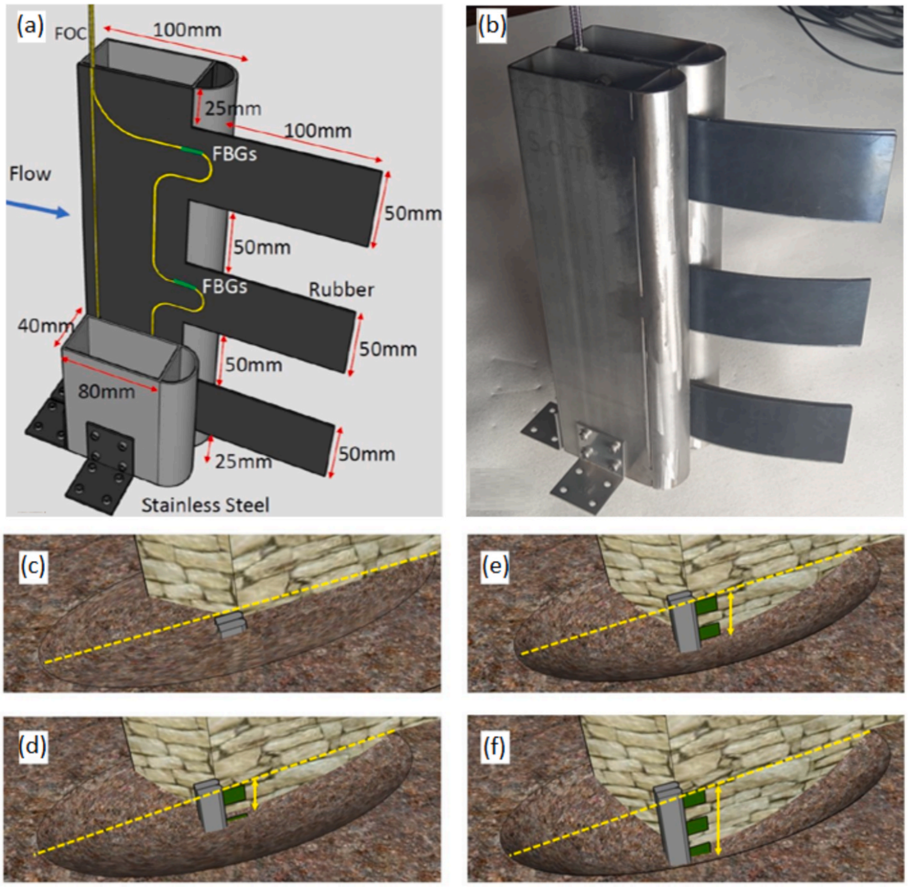

Fig. 1. FOSS – Cutaway diagram showing FBGs and dimensions and image of fabricated sensor pre installation: a) and b) show the design and real sensor; c) shows FOSS buried and no fins exposed; d) FOSS with top fin exposed; e) shows FOSS with top and middle fins exposed; f) shows FOSS with all fins exposed.

width of 11 m. This bridge spans the River Lagan (one of the main rivers in NI) and eventually flows through Belfast and into Belfast Lough.

In NI, historical buildings and structures are classified into four main listing grades based on their heritage importance: Grade 'A' (highest), followed by 'B+', 'B1' & 'B2' in descending order of importance. Listed status imposes legal protections controlling any proposed alterations or repairs and requires formal written listed building consent from the Historic Environment Division before any remedial or alteration work can commence. Regents Bridge was designated as a Grade 'B1′ listed structure in 1977 and is located within a conservation area. Consequently, any work proposed to the bridge must preserve the historic integrity and visual character of the bridge.

Regents Bridge is located within Dromore Town Centre, County Down. Access to the river is provided via a paved, tree-lined pedestrian footway from the main road, which is illuminated at night by streetlights as highlighted by the blue hatching (labelled 'B' in Fig. 3).

This public footpath provides convenient access to the bridge site, while the streetlights provide a potential source of power for the test equipment. A 1.2 m high timber fence mounted on top of an approx. 1 m high stone filled gabion basket wall bounding the side of the river, Fig. 3. This timber fencing provides a level of deterrent to pedestrians from accessing the river to the underside of the bridge without specialist equipment. The three remaining bounding edges (labelled 'C','D' and 'E' in Fig. 3) are private properties with high walls and 500 mm deep water at the river edge.

There are no water level riverbanks within this area of the river which further limits pedestrian access. A property access balcony located at point 'D' in Fig. 3 at road level provides a vantage point for viewing the upstream face of the bridge without entering the river.

The water level varies across the width, being deep enough (on average approximately 500 mm) to deter passing individuals from entering to explore but not too deep thus safe to access with waders. The river flow and depth vary depending on rainfall but is predominantly at a rate that does not pose a significant risk to inspectors. The riverbed material is a mixture of gravelly silt, some cobbles with occasional larger stones and localised deposits of bed material. This material is easily moved and placed, which is beneficial when installing the sensor and is representative of material that had previously scoured at this location. The cutwaters had

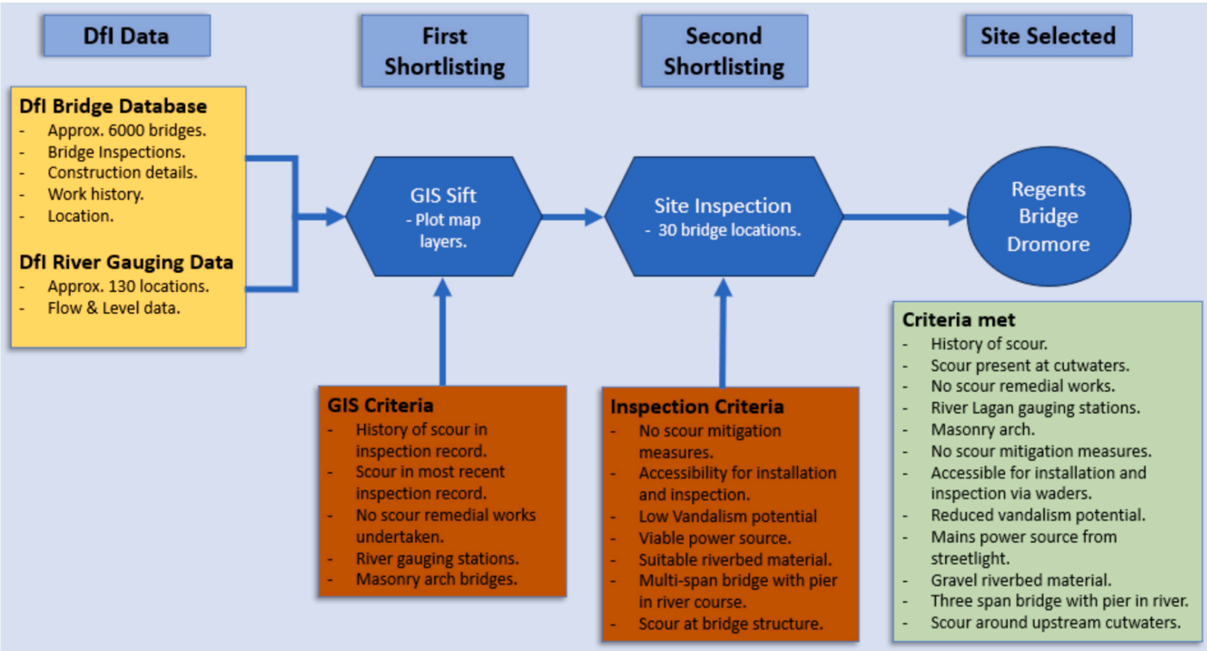

Fig. 2. Summary flow chart of site selection (DfI: Department for Infrastructure: GIS: Geographic Information System).

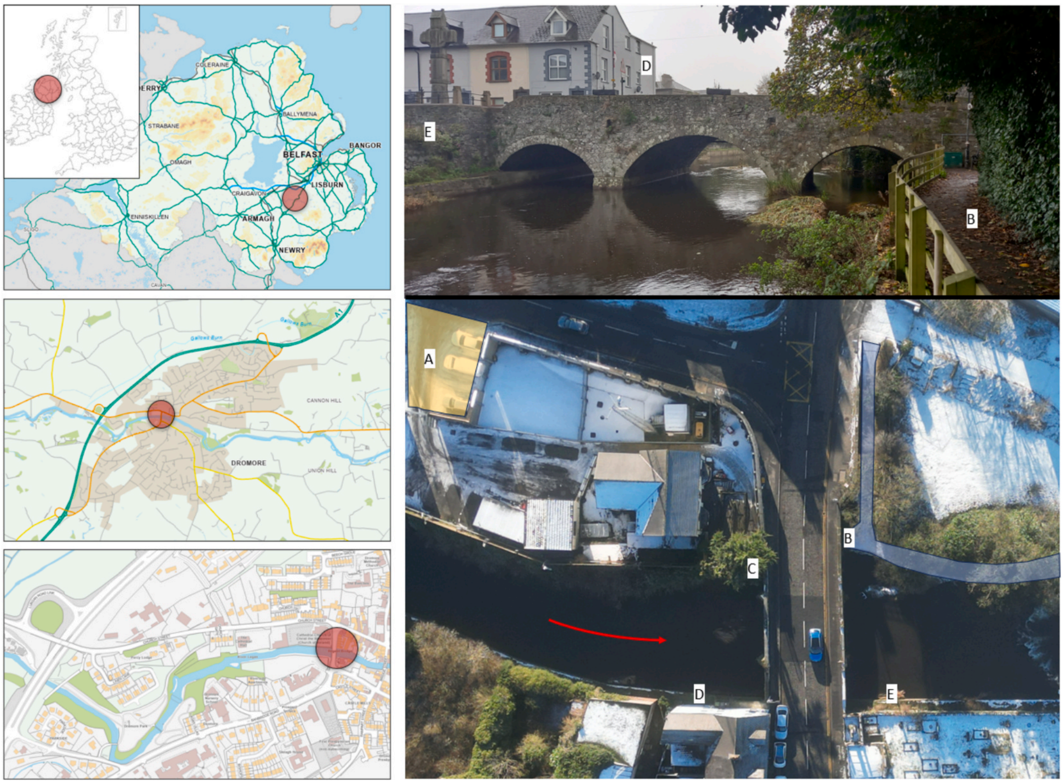

Fig. 3. Regent Bridge showing proximity of the car parking (A), illuminated surfaced pedestrian footway (B), property boundary's (C, D & E).

existing scour depressions, but no sign of undermining as previously recorded in the inspection history.

These physical and environmental conditions provide a certain level of deterrent to causal vandalism or public interference, while still providing ready access for the research team with conditions favorable for ease of installation and inspection.

The test site is located approximately 4.6 km downstream (3.6 km direct line) from the Lagan at Drumiller river gauging station (station ID:205008), owned and operated by DfI Rivers. This station sits within the '205 Lagan Quaille Hydrometric Area' which encompasses a catchment of 84.6 km^2 [27–29]. Operational since 1974, the station was upgraded in 1991 to a flat V shaped weir which changed the flow dynamics of the river, prompting a revision of the rating equation and data collected and stored digitally. The catchment geology consists of Silurian overlain with limited till [30]. The highest point of the catchment rises to over 500 m on the side of Slieve Croob in the Dromara Hills. The catchment predominately consists of grasslands and grazed uplands passing a largely rural setting before reaching Dromore.

2.4. Sensor installation and set-up

Site installation of FOSS was carried out on 12th February 2023 during a period of dry weather and low river levels (approx. 400 mm compared to an approx. maximum level of 1500 mm). A green lockable electrical cabinet was installed at the downstream side of the bridge, (Fig. 3b) and green marker labelled 'Power' in Fig. 4a This cabinet, powered from an adjacent streetlight, housed an isolator switch and provided a stable 240 V power supply to the testing equipment.

A stainless-steel waterproof enclosure was located approximately 3 m above the river edge, set back from a masonry river training wall and mounted to a reinforced concrete wall adjacent to the upstream spandrel (Fig. 3c and rectangular yellow marker labelled 'Data Logger' in Fig. 4a). Power was supplied from the green cabinet (as seen in Fig. 3 and rectangular green marker labelled 'Power' in Fig. 4a).

The mounting arrangement shown in (Fig. 4b–d) was designed to minimise both visual and physical intrusion above the bed level and waterline. This configuration reduces flow obstruction and limits the risk of damage from debris or entanglement. The rig's low profile ensures minimal visual impact on the listed bridge structure while maintaining unobstructed water flow around the sensor. A folded stainless-steel baseplate securely anchors the sensor, and a stabilising bracket at the top (Fig. 4d) provides structural support. This bracket also serves as a mounting frame for the FOC, offering protection during installation and operation. High-visibility tape applied to the sensor's top allows inspectors to visually confirm exposure during site visits without needing to access sensor data directly.

A weathered 25 mm by 25 mm by 3 mm equal angle iron was fixed to the stainless-steel bracket and baseplate with stainless steel bolts, which was deemed sufficient for short term monitoring. The FOC was secured to the inside corner of the equal angle by means of cable ties every 100 mm and a bead of clear silicon sealant to provide protection during the installation, implementation, data acquisition and sensor recovery phases.

A pre-existing scour hole on one of the upstream cutwaters was exploited as the location for installing the prototype sensor, shown in Fig. 4a–c. Loose material was removed from the base of the scour hole until compacted bed material was encountered and the sensor placed at the base.

Once in place, the test sensor mounting bracket and weathered equal angle iron section was fixed to the edge of the cutwater and a

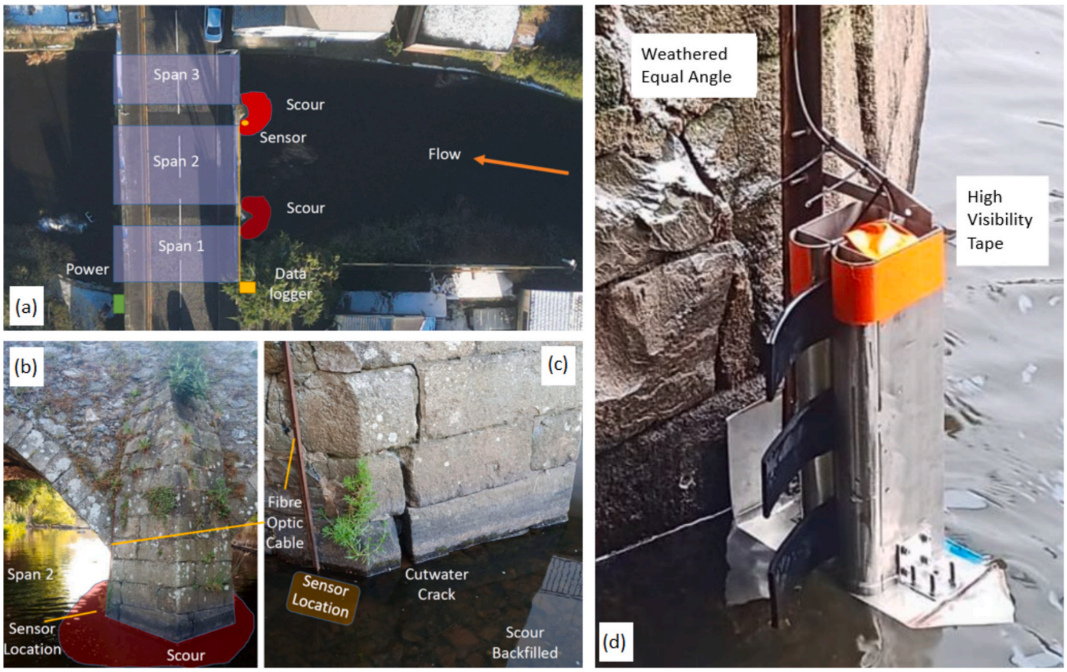

Fig. 4. Details of FOSS deployment a) Location of scour at upstream cutwaters. b) and c) sensor location showing minimal above water obstructions; d) sensor mounting rig.

mastic sealant used to encase the fixing points from water ingress. The equal angle extended to the point of the springing point (Fig. 4b), whereby it was deemed most likely to afford protection to the FOC from impacts from floating debris.

The unshielded FOC was secured to the spandrel face to the underside of the parapet copings and fixed along the parapet to the abutment and down to the stainless-steel cabinet marked as 'Data logger' in Fig. 4a.

During installation, the exposed sensor data traces were monitored to verify operational status. The three traces, corresponding to each sensor fin and detailed in Section 3, exhibited expected responses to movement. When agitated in situ, the sensors registered increased activity, thereby confirming full functionality and suitability for burial.

Localized deposited bed material within a 2 m radius adjacent to the scour hole was used providing representative material for that section of river and potentially the material that had previously been displaced during previous scour events. This material consisted of a mix of sand, gravel with some small cobbles and organic matter and was carefully placed around the sensor.

Fig. 5 shows the layout of the equipment within the stainless-steel cabinet, as well as the flat traces of the three buried fins.

As the fins were buried, the traces progressively flattened out indicating reduction of movement and therefore capturing the infill process. Once FOSS was completely buried, all three traces flattened out as expected and as observed in previous laboratory tests.

2.5. Visual monitoring

The river under normal conditions flows with brown tinted translucent water and the riverbed surface is visible in bright conditions. In deeper water and with surface turbulence on the water it is challenging to see distinct details. During higher flows the water can become opaque with suspended materials such as sediment. The prototype FOSS is largely constructed from stainless-steel which is clearly visible in the translucent water. This stainless steel and the bright fluorescent orange tape allowed observation of the top of the FOSS even in relatively dull conditions from above. Some distinctive cobbles (bright red tumbled chunks of red brick) were placed near the FOSS, to act as a quick visual aid: the eventual movement of these cobbles would indicate the movement of the bed material.

The sensor was fully buried at the start of the implementation phase with only the weathered 25 mm equal angle section that extended to the arch springing point plus the FOC running to the stainless-steel cabinet being visible. Once installed, during the implementation phase, regular visits (weekly or after rainfall) visually checked from the bridge deck and access balcony for changes of the FOSS fluorescent orange tape or stainless steel. Observations referred to the distinctive red brick cobbles and if these had not moved, then scouring and infilling was unlikely to have occurred at this location. These quick visual checks supplemented longer detailed checks to ensure the FOSS was fully operational. These longer checks required access into the river with waders, to check the equipment within the stainless-steel cabinet was still running and recording data. Then, a closer visual inspection was conducted around the cutwaters and the immediate vicinity of the FOSS sensor to check for scour and any signs of the buried sensor being exposed.

3. Results

The data acquisition unit was set to a scanning rate of 1 kHz and file saving, and storage was triggered at 5 min intervals to the computer's hard drive. FOSS saved daily data files, recording the Timestamp, Top Strain, Middle Strain and Bottom Strain to an external hard drive. On completion of the data acquisition phase of the site trial the data files were downloaded to a separate computer for processing. Weather data was obtained from DfI gauging stations and open-source weather station data uploaded to www.wunderground.com. Data was collected from various sources as outlined in Table 2 from FOSS sensor data, DfI held data and third-

Fig. 5. Steel cabinet showing data acquisition equipment layout.

party weather station data.

3.1. Initial findings

For the purposes of this paper there are three distinct time periods referred to as phases as detailed in Section 2 Table 1, which are the ‘Implementation Phase’, ‘Data Acquisition Phase’ and the ‘Sensor Recovery Phase’.

The implementation phase corresponds to when the sensor was first installed on site on 12th February 2023 and started recording, however due to a hard drive malfunction in the onsite computer, all data collection up to 18th October 2023 was lost during this phase. During the Implementation phase visual inspections revealed that the red brick cobbles used as informal markers had not moved and the FOSS sensor remained buried. On occasion debris trapped on the cutwaters needed to be carefully removed to permit a visual inspection to confirm nothing had been exposed. These informal markers gave confidence that no scouring or infilling is likely to have taken place around the sensor during this time. During the Implementation phase, the FOSS was exposed to three named storms. These storms are not presented in this paper as there is no corresponding data from the FOSS sensor to directly compare with. On replacing the computer and starting the data acquisition phase, the three fin traces appeared fully operational, indicating that the sensor had survived this implementation phase.

During the data acquisition phase and sensor recovery phase, visual inspections revealed that the red brick cobbles used as informal markers had moved and the top of the FOSS was visible, indicating scour had occurred around it during these phases of this test. It was noted that during higher-flow periods in the river, during storm events, floating debris, such as tree stumps and vegetation was observed to impact the cutwaters and, on occasion, get caught on both cutwaters. Once the water levels and flow in the river had reduced to a safe level that permitted safe entry by operatives in waders, the area around the sensor was investigated within touching distance and any trapped debris at the cutwater was carefully removed to inspect the sensor. The stainless-steel sensor body was visible, and the FOSS fins seen to move freely in the flow, which indicated that it had physically endured the effects of debris impact without any visible signs of damage.

Scour was located around both the upstream cutwaters, and the sensor was located centrally within the main depression, to a similar extent only slightly deeper as when it was installed (as shown in Fig. 4). Given that this depression was originally a scour hole that had been artificially infilled during the installation of this sensor, it was not unexpected that this material would wash out again in a period of flood.

The conclusion was that the sensor had physically survived the scouring event and that it had not been dislodged or dented by passing debris. It was also clear that a scour event had occurred at the expected location, and the sensor was installed in the right position to capture this event. Despite the minimal level of mounting points to the structure, the physical robustness of the sensor was very encouraging and the presence of scour during the data acquisition phase validated the choice of location as a suitable test site.

3.2. Storms data

The UK Meteorological Office (Met Office) publishes weather warnings of various grades from Yellow, Amber and Red depending on the severity of the event. If a weather event is deemed likely to bring significant impacts to the UK, then it may become a named storm [30].

The monitoring period included two named storms, Babet (18th-21st October 2023) and Ciaran (1st-2nd November 2023). Weather station data was obtained for October and November 2023 for the test location via a weather monitoring station located approximately 800 m Southeast from the test site in Dromore. This data provided a plot of Precipitation rate and Precipitation Accumulation Total for October 2023 (Fig. 6).

Flow rate and stage level data was downloaded from the Lagan at Drumiller Gauging station for the same months; the period between the 18th and 31st of October (corresponding to the FOSS data acquisition phase) is plotted in Fig. 7.

Records of the stage levels from this gauging station typically range between 0.17–0.248 m for the period following the original installation of the sensor in February 2023.

During the storm events Babet and Ciaran, there are three occasions where the stage levels exceeded the bank full level of 1.24 m up to a level of 1.907 m (Fig. 7). During the storm events fluvial flooding was experienced along the Lagan River. The flow rate recorded in

Table 2
Data sources.

Source	Type	Accuracy
FOSS	Timestamp	Day Month Year Hour Minutes Seconds (DD:MM:YY:HH:MM:SS)
	Top Strain	microstrain (με)
	Middle Strain	microstrain (με)
	Bottom Strain	microstrain (με)
DfI	Rainfall	Millimeter (mm)
	Stage Level	Meter (m)
	Flow Rate	(m^3/s)
	Bank Full Level	Meter (m)
https://www.wunderground.com	Precipitation rate	Inches/Hour (In/h)
	Precipitation total	Inches (In)

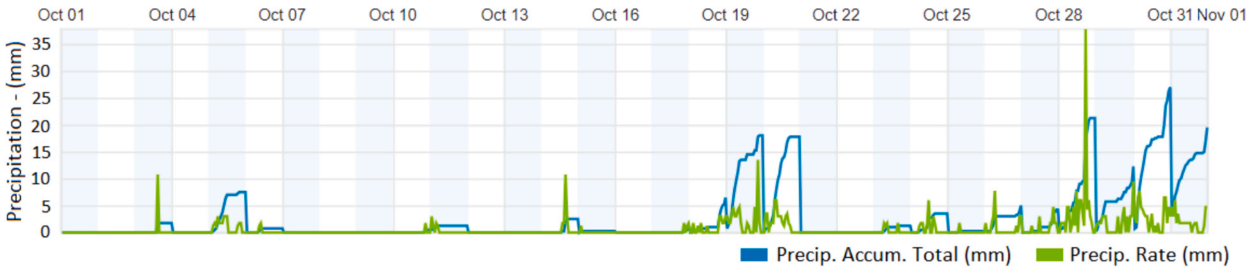

Fig. 6. Precipitation rate and total versus time.

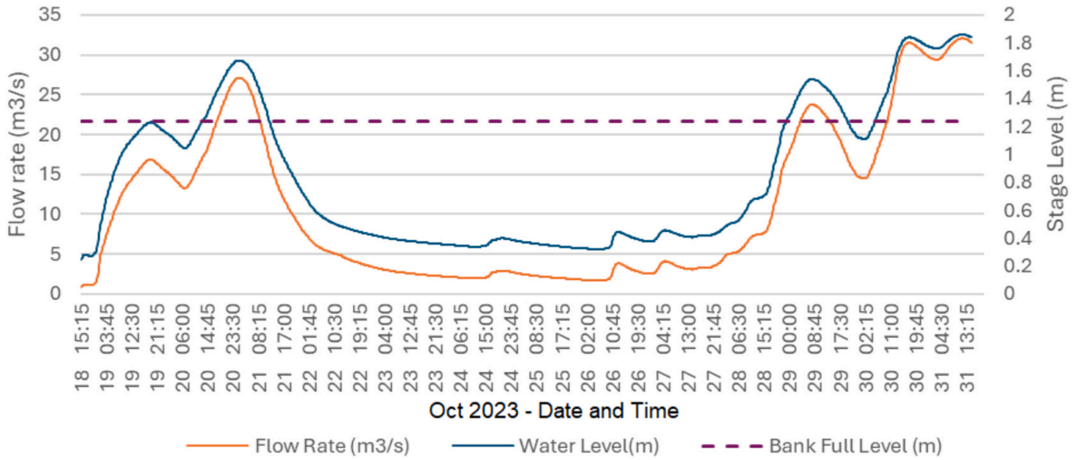

Fig. 7. Flow rate and stage level verses date and time.

Drumiller gauging station increased from around 1 m^3/s on the start of the 18th October to a peak of 27 m^3/s on the 20th October, then reverted back to approx. 2–3 m^3/s following the event before returning to 32 m^3/s during the second named storm event (Fig. 8).

Daily rainfall levels from the weather station were plotted on the same graph as the stage level data for October 2023 and the two named storm in Fig. 8.

The collected data demonstrates that the stretch of the Lagan River catchment at Regents Bridge experienced increased rainfall and subsequently increased flows and river water level during the two named storms. This result is not trivial, since a named storm in a region does not necessarily mean that all rivers will experience increased rainfall or rising water levels should the rain not fall within the associated river catchment area.

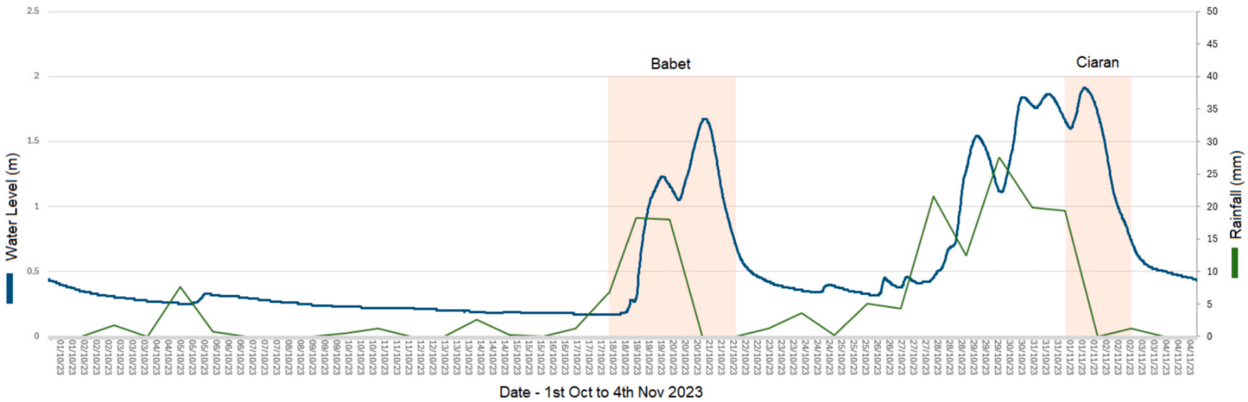

Fig. 8. Rainfall (mm) and stage level (m) for the period between 1st Oct to 4th Nov encompassing two named storms, Babet and Ciaran.

3.3. Data analysis

Separate daily data files were saved and retrieved from site covering the data acquisition phase between 19:15 on 18th October 2023 to 23:00 on 31st October 2023.

To analyse the sensor response during the storm events, the raw data was recorded at 1 kHz. A third-order Butterworth high-pass filter (cut-off at 2 Hz) was applied to 10 s batches (10,000 samples) to remove slow-varying thermal effects while retaining dynamic oscillations caused by fin exposure. The 10 s interval was chosen as a balance between computational efficiency and responsiveness to scour induced vibrations. The filtered data is converted from relative FBG wavelength data to strain using a gauge factor of 0.78 [31].

The primary scour indicator used in this study is the standard deviation (σ) of strain within each 10 s batch. This value is a measure of the amount of oscillatory dynamic variation of the strain around the mean strain rather than static strain shift for each Fin of the FOSS sensor. The individual field data files were combined to form one continuous dataset which included the date and time, top Fin strain standard deviation, middle Fin strain standard deviation and bottom Fin strain standard deviation for each 10-second interval. Fig. 9 shows this continuous dataset plotted alongside gauging station flow rate data.

Fig. 9 shows a change in dynamic strain over time in the three fin sensors, as the flow rate in the river increased during storm Babet. As Babet ended on 21st October, the flow rate reduced to almost normal levels again around 2–3 m^3/s, Fig. 7. This flow rate coincided with the fins movement decreasing and relatively stabilising. The top fin broadly follow the same profile as the other two fins however, seems to stabilize in a higher σ strain position relative to the other two fins (Figs. 9 and 10).

When a fin is buried, dynamic strain remains stable (low variability). Once exposed to flow, the fin vibrates, increasing variability. Thus, standard deviation provides a robust indicator of dynamic activation, independent of baseline drift. While a moving average filter could smooth the raw signal, it would primarily capture mean strain changes, which are less sensitive to scour-induced oscillations.

When Storm Ciaran approached, the rainfall increased (Figs. 7 and 8), resulting in the flow rate increasing. It is possible to attribute peaks in the water level and flow rates in the river with responses picked up in the three fins such as seen in Fig. 9. Water level peaks clearly preceded peaks in the top fin trace and to a less noticeable extent the middle and bottom fins. Fig. 9 shows the signal from the fins increased up to the end of 31st October, when the sensor stopped unexpectedly, and no more data was recorded.

Fig. 10 shows the three fins plotted separately while still sharing the same x-axis.

Except for a period around the 21st October 2023, the magnitude of the dynamic strain in the three fins broadly conforms to the top fin showing the biggest magnitude followed by the middle fin and the bottom fin showing the smallest dynamic strain response. The middle and bottom fins follow a similar overall response during the data acquisition phase indicating they were still exposed to flow but exposed to relatively reduced velocities between storm events. The top fin appears to initially follow a similar response to the other fins, however around 07:15 on 21st October it remains at a higher σ strain position relative to the other two fins. Despite the top fin not mirroring directly the same plots as the middle and bottom fins, the general response is similar with it registering similar peaks noted in the middle and bottom fins from the 29th October 2023 onwards.

Figs. 9 and 10 show that all three fins responded to the storm Babet event on the 18th October, indicating that the scouring event

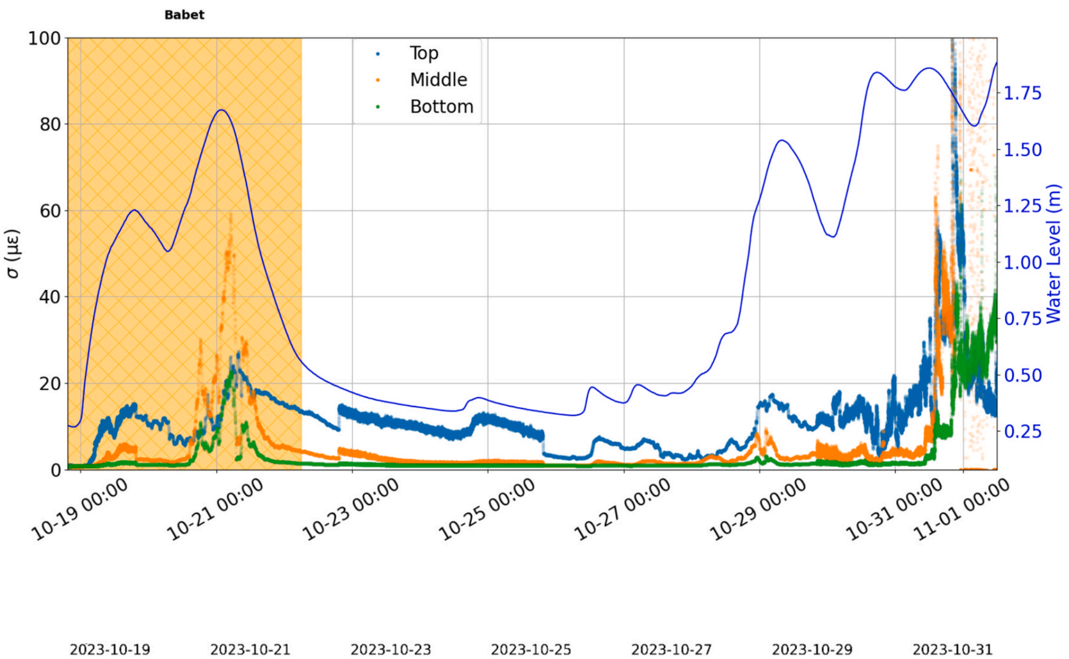

Fig. 9. Gauging station and sensor data for 18th–31st Oct 2023.

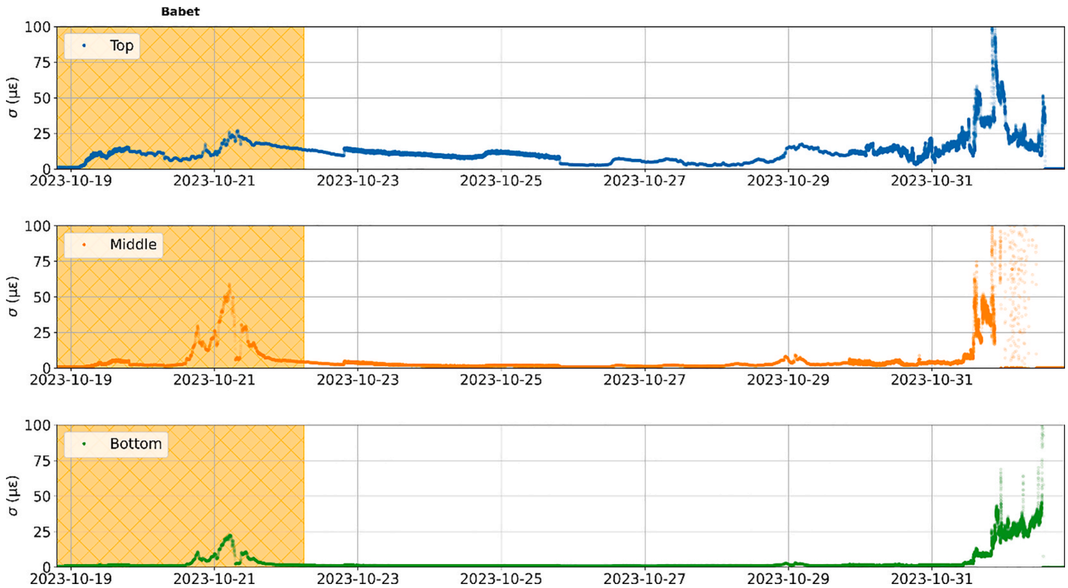

Fig. 10. Strain plotted against time for the three fins of FOSS (bottom, middle, top) separately.

occurred quickly across the three fins.

Focusing on the data for the 19th October, when the three fins appear to activate first, Fig. 11 shows that there is a clear delay in activation between the three fins.

Fig. 11 shows the sequential activation of the fins during storm Babet. The top fin activates first, followed by the middle fin then the bottom fin as expected. When considering the point when the sensor std μ strain has risen above 1.3, as a point deemed as statistically significant in this dataset, the lines correspond to the following times: Top – 2023–10-19 03:00:00, Middle – 2023–10-19 06:00:00 and Bottom – 2023–10-19 09:30:00 to the nearest 30 mins. The threshold of 1.3 μstrain (standard deviation) was determined empirically by analyzing baseline variability during burial and comparing it to activation periods in laboratory calibration tests. This value represents a statistically significant deviation from the buried state (mean ± 3σ of baseline noise). After the top fin activates, the second fin activates approximately 3 h later, followed by the bottom fin about 3.5 h after that. This progression of fin activation gives a good indication that the sensor functioned as designed in tracking the progression of scour at the bridge upstream cutwater.

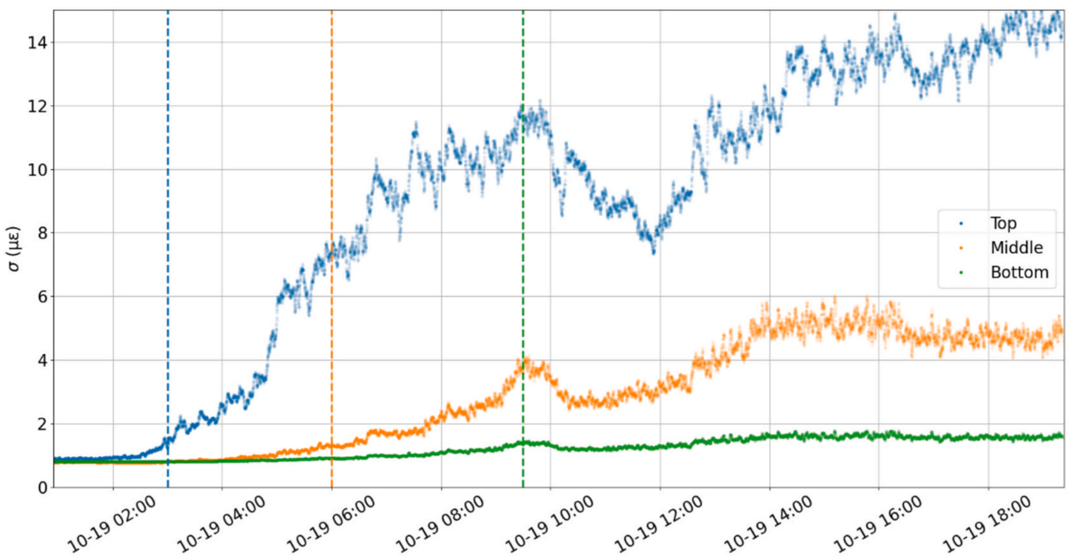

Fig. 11. Plot of data corresponding to the first activation.

4. Discussions

One possible reason that the top fin displayed a greater strain response relative to the other two fins could be that it was displaced from its natural resting position possibly due to debris, as illustrated in Fig. 12.

If the top fin was pressed outwards by debris, it would have been more exposed to vortices generated by the sensor's bluff body shape (Fig. 12), potentially explaining why its response 'B' exceeded the middle and bottom fins' response 'A'. This theory was tested and validated using a second undeployed sensor. One fin was manually displaced and the traces observed indicated a similar trace as observed in this study.

As noted in Sec. 3.1, on occasions debris was removed from the cutwater when visually inspecting the sensor. It is possible that the response in the top fin reverted closer to the other fins plots again around 29th October 2023 (Figs. 9 and 10), when a piece of debris was dislodged, allowing freer oscillation. However, without detailed records of when and where debris was removed nor the precise location or whether it was pushing the top fin outwards into the flow, this rational cannot be fully validated.

Another possibility is that the top fin was slightly more exposed to the flowing water whereas the middle and bottom fins were partially sheltered from passing flow by being sheltered within the scour hole, reducing the fins dynamic response to flow, which is another area for further investigation.

As outlined in the previous sections, the FOSS sensor captured strain data corresponding to all three fins, to detect progressive scour. The displacement of the fins results in a change in the recorded strain, indicating erosion of the surrounding bed material, likely due to the continuous hydraulic action of flowing water. The results show that all three fins appear to move or became exposed sequentially within approximately 6.5 h on the 19th October 2023 (Fig. 11). This rapid activation may be attributed to the minimal fin spacing and unconsolidated fill around the sensor during installation.

The FOSS sensor's ability to track the development of scour down the sensor from top to bottom fins during a named storm event demonstrates its capability to detect scour in real time under real world conditions. Given the sensor fins were installed to a known point relative to the cutwater and bridge foundations, their deployment provides actionable insights for bridge managers, enabling early warnings of scouring and aid in the decision-making process for its management.

Unfortunately, it was not possible to determine if the process of infilling occurred during this trial prior to the sensor ceasing

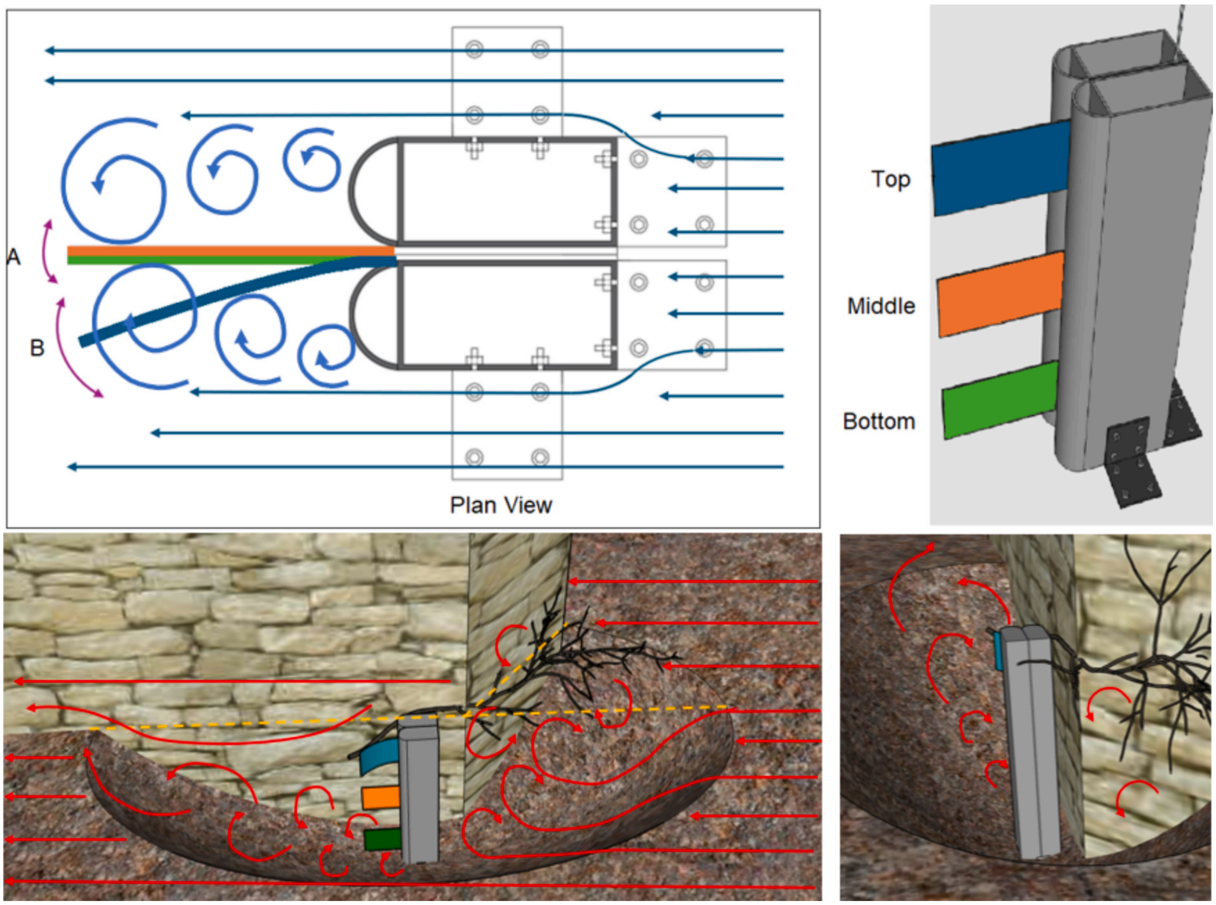

Fig. 12. Potential explanation of top fins greater strain response due to the presence of debris.

recording strain on the 31st October 2023.

The sensor remained in place until its recovery on the 18th October 2024, almost a year later after it ceased recording strain (Fig. 13), referred to as the sensor recovery phase.

The sensor recovery phase provided valuable insights into how a longer-term deployment would impact on the mounting arrangement and sensor's resilience in a riverine environment, particularly under debris loading. Upon retrieval, minor bimetallic corrosion was observed between the fixing screws, support brackets and the mild steel angle section, though it did not compromise the sensor's attachment to the cutwater. The silicone cover encasing the FOC remained intact, however the glued fins showed evidence of delamination (Fig. 13), exposing the embedded FBG to grit and sand, likely resulting in abrasive damage and thus contributing to the sensor failure.

4.1. Operational challenges identified

Several operational challenges were identified during this trial, which will inform recommendations for future deployments:

1. Installation Data Oversight: During site installation, the sensor traces were observed flattening out as they became buried, simulating the infilling process. These traces were not recorded in this trial. Future deployments will ensure these traces are recorded for analysis.
2. Hardware Failure Data Loss: Corruption of the original site computer's hard drive resulted in the first four month's data being unrecoverable, referred to as the implementation phase. A more robust computer system has since been installed to minimize the likelihood of hard drive failures again.
3. Sensor Range Limitations: Rapid development of scour at the bridge cutwaters resulted in the fins activating within a 6.5 h period. This FOSS setup has a vertical sensing range of only 250 mm, consideration to be given to increasing the spacing between the fins or deploying to another site where the rate of scouring is anticipated to be slower.
4. Fin Delamination: Glue used between rubber fin layers failed resulting in the fins delaminating and exposing the FBG to sand and grit resulting in the failure of the sensor. Future deployments necessitate the improvement of these fins to either use harder wearing glue or investigate methods of embedding the FGB within a single layer of rubber molded around it.
5. Mounting Arrangement Corrosion: Whilst not a significant issue during this trial, for long-term deployments the corrosion noted in the mounting arrangement could pose a challenge. The corrosion resistance could be improved by using all stainless-steel components and fixings. Consideration is needed of how to minimize the visual impact if installed on listed structures.

4.2. FOSS strengths demonstrated

Despite the challenges outlined in 4.1, they can be addressed in future studies to enhance the effectiveness of FOSS. Nevertheless, the trial demonstrated several key strengths of FOSS and the test site used:

1. Scour Detection: Results demonstrated FOSS's ability to detect the presence and development of scour at the location of the cutwater in real-world conditions.
2. Hydrological Responsiveness: FOSS exhibited an immediate response to hydrological variations, correlating well with river gauging station flow and rainfall data. The sensor detected scour following storm 'Babet' and continued to reflect flow variations to subsequent storm Ciaran, validating its potential for real-time monitoring.
3. Sensor Resilience: FOSS remained physically intact and in position despite exposure to the riverine environment and likely impact from be passing debris during storm events. Failure of the sensor was attributed to the glue used in the fins, which can be readily resolved.
4. Resilient Power Source: During fluvial flooding at the test site, the power cabinet was partially submerged but remained operational. This outcome demonstrated the power source to be robust against similar or less severe storm conditions in future.
5. Resilient Equipment location: The stainless-steel cabinet housing the data logger and computer equipment was located above the high-water level and remained unaffected, during major storm events. The cabinet was not readily accessible by the public and did not experience any tampering or vandalism, validating its placement.
6. Site Suitability: Regent Bridge proved to be an effective test site for evaluating scour instrumentation in a real-world setting.

4.3. Future research

Initial data analysis confirmed a strong correlation between sensor output and hydrological data. While elevated river flows or water levels do not always result in scouring at a structure, FOSS's response to storm Babet and subsequent flow variations suggest it can effectively capture such scour events.

An initial sampling rate of 1000 Hz was selected to capture very minor levels of scour and infilling, since it was uncertain whether significant scour would occur during the testing phase. This high rate provided fine grained data but generated significant daily data file sizes. On reviewing decimation data, it was concluded a reduced sampling rate of 1 Hz would still be effective for long-term monitoring while significantly reducing the data storage and processing requirements. This trade-off, however, limits the potential for advanced post-processing techniques, such as correlating sensor vibrations with flow dynamics. Further laboratory testing is required to fully explore this opportunity.

Fig. 13. Images showing the recovered VFS including the delaminated fins and exposed FBG. Top fin deliberately splayed open to show FBG.

The sensor used in this site trial was an early-stage prototype used for proof of concept, which lacked remote access capabilities. As a result, an onsite operative was required to visit the site and observe the traces on the onsite computer. Nevertheless, the results demonstrate that this data, if relayed remotely, would have been capable of providing the real-time output desired, reinforcing the potential of this system for future remote monitoring applications.

Future mounting rigs will incorporate refinements in its design, including addressing the longer-term corrosion effects noted in this trial, using only stainless steel for the sensor and the mounting bracket used to attach to the structure. These improvements will enhance durability and reduce maintenance requirements for extended deployments.

5. Conclusions

This study aimed to present the initial development and field deployment of a novel scour sensor named FOSS (Fibre Optic Scour Sensor), designed to detect and record scour and infilling processes in real-time at a representative bridge structure. The trial aimed to evaluate the sensor's operational performance under real-world hydraulic conditions and its resilience over an extended deployment period.

The key findings from the trail include:

1. Site Suitability: The selected bridge location proved to be an effective test site, offering practical advantages such as ease of installation, accessibility for visual inspection, and protection from vandalism. The site also provided a dynamic hydraulic environment conducive to evaluating scour instrumentation.
2. Scour Detection: Scouring at the test location was anticipated due to the artificially placed unconsolidated bed material during sensor installation. The sensor successfully detected the development of scour during Storm Babet, with sequential activation of the top, middle and bottom fins within a 6.5 h window. This result confirmed the sensor's responsiveness to hydrological changes and its ability to track scour development in real time.
3. Sensor Durability: Despite prolonged exposure to riverine conditions and debris impact, the sensor remained securely attached to the cutwater for over 20 months and effectively captured scour progression during Storm Babet, demonstrating its robustness and reliability.

While FOSS demonstrated promising performance, this trial represents an early-stage prototype. Several enhancements are recommended prior to future redeployments:

1. Fin Construction: Embedding FBGs within a single molded rubber unit could help mitigate delamination and protect the sensing elements from abrasive damage.
2. Remote Monitoring: Integrating wireless data transmission, such as linking the sensor to an online dashboard via data SIM, would enable remote access and real-time monitoring. Reducing the on-site visits.
3. Comparative Evaluation: Benchmarking FOSS against conventional scour monitoring technologies would provide valuable insights into its relative performance and operational efficiency.

4. Material and Mounting Improvements: Utilizing corrosion-resistant materials and refining the mounting arrangements will enhance long-term resilience whilst cognizant of the visual impact on heritage listed bridges.

Incorporating these improvements in future iterations will contribute to the development of a more robust, scalable and field-ready system. FOSS has the potential to provide bridge owners and infrastructure managers with timely, accurate scour warnings, enabling proactive maintenance and risk mitigation strategies.

CRediT authorship contribution statement

Kristopher Campbell: Writing – original draft, Investigation. **Maria Pregnolato:** Writing – review & editing, Supervision. **Raj Kamal Arora:** Formal analysis, Writing – review & editing. **Su Taylor:** Supervision. **Remco Nieuwland:** Writing – review & editing, Software, Formal analysis. **Piet van Andel:** Formal analysis. **Myra Lydon:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ymssp.2026.113868.

Data availability

Data will be made available on request.

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