A new prototype of Fibre Optic Sensor (FOSS) to monitor bridge scour

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Abstract

Bridges play a key role in the transportation network system and are vulnerable to various natural hazards. For bridges constructed over rivers, scour is one of the major causes of bridge failure. With the growing impacts of climate change, both the intensity and frequency of flood events are increasing, raising significant concerns regarding the safety and maintenance of bridge infrastructure. This study presents a method for remotely monitoring scouring which uses a Fibre Optic scour sensor based on Fibre Bragg Grating, named FOSS. The sensor comprises three sensing elements (fins), which are embedded at different depths. The system operates on the principle that, when erosion occurs, the movement of these fins generates a measurable response, indicating the depth of erosion. This paper presents the sensor's characteristics and shows preliminary findings from a field deployment on a bridge in the Northern Ireland region.

Keywords: Fibre Bragg Grating (FBG), bridge network, scour, sensor, fibre optics

1 Introduction

Bridges are important structures that help connect roads, rivers, valleys, and other areas, making them key to transportation networks. Because of their importance, bridge owners are responsible of keeping them in adequate service and safety condition. This task is challenging since these bridges are exposed to continuous action of different natural hazard.

In Europe and in the UK, there are many bridges that exceed their design life as specified in Eurocode or British Standards of 100 or 120 years [1]. This group includes several bridges in Northern Ireland that are still in use today, of which the 53% are masonry bridges. However, many of these older bridges do not have detailed design records and are built without considering future challenges like heavier traffic, severe flooding, or climate change [2,3].

Scouring is defined as erosion of soil around the bridge foundation due to the continuous action of flowing water and considered the leading cause of bridge failure worldwide [4]. Scour includes different types, such as general scour, local scour, or construction scour. Scour mostly occurs around the bridge foundation (local scour) and results in reducing the load carrying capacity of structure which can ultimately lead to the failure of the entire structure [5, 6]. Therefore, it is essential for bridge owners to assess scour depths at critical bridge locations. Identifying the scour depth at the area of concern can help the bridge owner to deploy countermeasures, e.g. to enhance the capacity of structure or avoid trapped debris.

Many efforts have been made to develop sensors that help monitoring and reducing the risk of scour around bridge piers [7, 8, 9, 10, 11, 12]. While some methods are capable of measuring scour depth in real time, they still face certain limitations. These limitations highlight the need for a new type of scour sensor that can accurately track scour depth in real time and is also simple to install and use.

Building on this need, this paper presents the early development and initial findings of a Fibre Bragg Grating (FBG) based fibre optic sensor, called FOSS (Fibre Optic Scour Sensor), installed at a bridge site in the Northern Ireland region.

2 Sensor development

The prototype version of the scour sensor developed was first tested in laboratory and showed promising results [13]. This paper showcases the deployment of the developed sensor in a real pilot (in-field) and its preliminary results.

2.1 General overview of FOSS

The developed sensor consists of a fibre optic cable with three FBGs, each placed between two thin rubber layers to form three individual fins positioned at different depths (Fig. 1). These fins can detect any changes by generating signals when they shift from their mean position. The entire system is enclosed between two stainless steel sections, forming a bluff body that shields the optical components. FOSS is capable of capturing real-time data related to both the scouring and infilling processes which may occur during floods.

2.2 Selection of site

The Department for Infrastructure (DfI) records the construction details, construction date, span details and inspection data in an organised bridge network database. Additionally DfI also collects river levels and discharge from approximately 150 gauging stations located around Northern Ireland region.

An appropriate location for deploying the prototype was selected using the following factors:

1. The bridge should be a multi-span masonry structure.
2. The site has to be easily accessible.
3. The bridge should have a known history of scour issues, with no previous remedial works or countermeasures in place.
4. The site should have nearby gauging stations to record flow level and flow discharge.

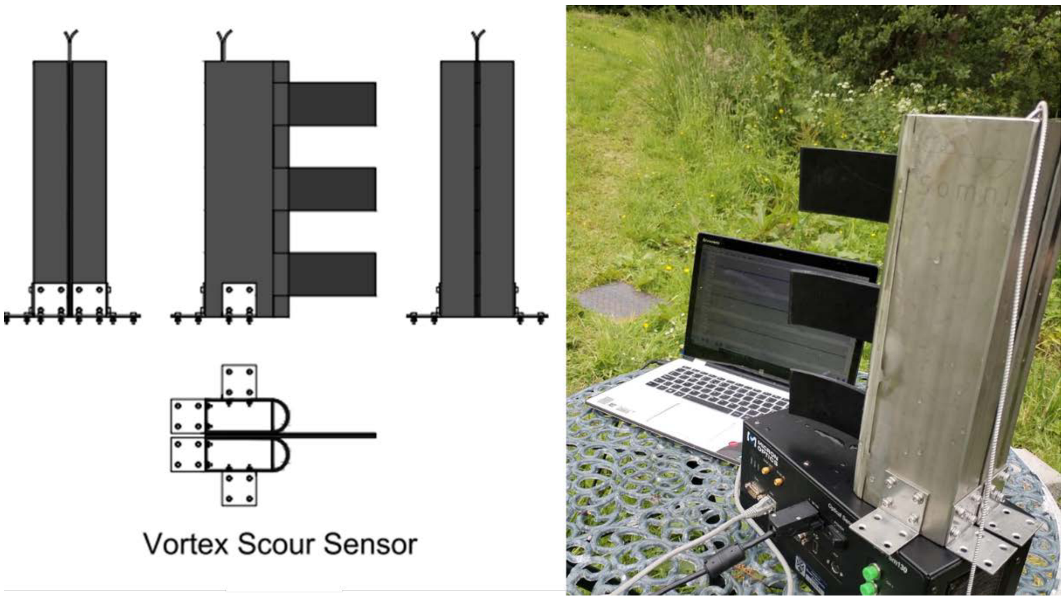

Figure 1. The FOSS Sensor with the three fins, each containing a FBG sensor

Figure 2. Regents Bridge

5. Additional considerations such as the risk of vandalism, availability of nearby power supply, and any potential issues from debris or log impacts were also looked.

Considering the above criteria and using Geographic Information System (GIS) map layers, Regents Bridge in Dromore (County Down, Northern Ireland) was chosen as the testing deployment site (Fig. 2).

The selected bridge is a 3-span masonry arch over the Lagan river and was built in early 19th century; it has a total length of 21.4 m and width of 11 m. Regents bridge was listed in 'B1' category (from 'A', 'B+', 'B1', 'B2' grade) for its historic importance; hence, interventions must not impact negatively the historic integrity of the bridge.

The average water level at the bridge site is approximately 500 mm, which is relatively shallow. Even during flooding events, inspectors can safely assess the bridge on foot without facing significant risks from high water levels. The riverbed material is a mixture of gravelly silt, some cobbles with occasional larger stones and localised deposits of bed material. This material can be easily moved during the installation of the sensors. The site also has a gauging station at 4.6 km downstream.

2.3 Sensor installation and setup

The installation of scour sensor was done in February 2023 (dry weather, approx. 400 mm water level). A green lockable cabinet powered from nearby street light is installed at the downstream side (Fig. 2). It has an isolator for providing steady 240 V power supply to testing equipment. A stainless steel water proof enclosure was set 3 m above the river edge set back from a masonry wall mounted to a RC wall closed to span 1 ("data logger" in Fig. 2).

A folded stainless-steel baseplate provided a secure mounting for the sensor and a stainless-steel bracket stabilised the top of the sensor. The steel brackets also act as a frame and provide the protection to the Fibre optical cable (FOC). A High-visibility tape on the sensor is applied which allows the inspectors to visually confirm its exposure without checking data outputs. A stainless steel angle section is used to secure the FOC by means of cables applied at every 100 mm.

The setup was installed in a pre-existing scour hole by removing the necessary loose material from the bottom. The unshielded FOC was securely connected to the Data logger cabinet. Data acquisition was initiated and the exposed sensor data traces observed to check they were operational. The three fins now detect movement when disturbed in place. The surrounding material (within 2 m radius) was carefully backfilled, ensuring the top fin remained embedded beneath the surface. After the deployment of the sensor all the three fins showed flat traces which is quite evident. The scanning rate was initially set at 1000 kHz, then reduced to 1 kHz, with data recorded every 5 minute.

2.4 Visual Monitoring

Under normal conditions, the river remains relatively clear, allowing partial visibility of the riverbed, which makes the FOSS clearly visible during installation. However, during extreme conditions, the water turns opaque due to suspended particles like sediments. To address this issue, a fluorescent orange tape was affixed to the FOSS. The combination of this high-visibility tape and the reflective stainless steel enhances its detectability even in low-visibility scenarios. The site was visited every week and always after a period of rainfall. The initial scouring was visually checked due to movement of red brick cobbles in the vicinity of sensor. The detail check was done by entering into the river to ensure, whether FOSS is fully operational or not.

3 Results

The FOSS data is saved on all three strain fins sensor (top, middle, and bottom) to an external hard drive. This data was later transferred to another device for post processing. Weather data was also obtained from DfI.

Based on the UK Meteorological weather report, the monitoring period included two named storms, namely Babet (18-21, Oct 2023) and Ciaran (1-2, Nov 2023). A weathering station approximately 800 m southeast to the site in Dromore was used to obtain the October and November 2023 precipitation data. Based on the data provided there are three time instance where the water level exceeds the full level of 1.24 m. Also the maximum flow rate during these two storm were approximately 27 m^3/s and 32 m^3/s respectively.

3.1 Initial Finding

The initial displacement of the red cobbles was detected by the top fin of the FOSS sensor. During periods of heavy flow, it was noted that floating debris or logs could interfere with the cutwater. Once the water level receded to a safe range, the area surrounding the sensor was carefully inspected without disrupting the nearby region. It was confirmed that the fins remained intact which validates the durability of the used sensor.

The daily data file retrieved from the site covered the period between 18-31, Oct 2023. The response of the sensor was clearly visible at the chosen frequency. The data files was combined to form one continuous dataset which includes date, time and strain at all three fins and was plotted with respect to flow rate (Fig. 3).

Figure 3 shows that variation recorded in all three fins during the storm period. As the storm period approaches, the response initially increases but gradually decreases over time. A vertical offset is provide in the figure to clearly distinguish the result from the three sensors. The top and bottom fins

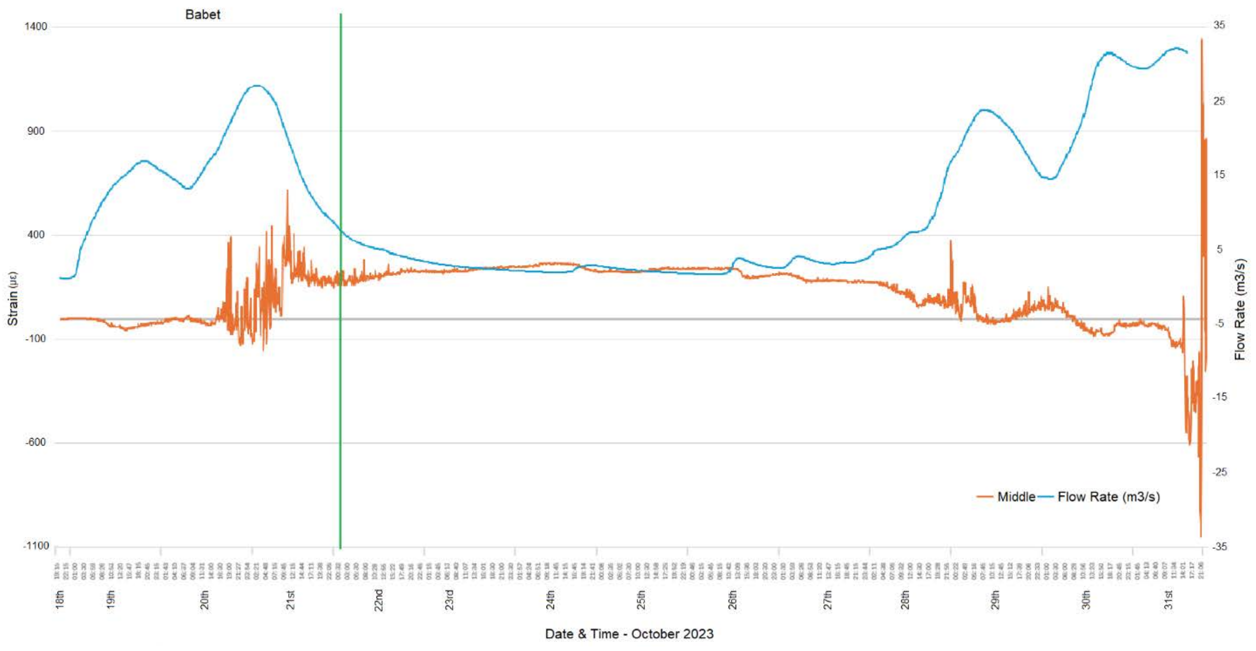

Figure 3. Strain plotted against time for the middle fin during storm Babet

followed a similar pattern with similar response in both negative and positive direction.

The middle fin shows a pattern similar to the other fins. However, at 7:15 on 21st October 2023, it exhibits a significantly larger shift toward the positive side of the strain plot. This change denotes a possible shift from its average position. One potential reason for this could be the presence of debris near the middle fin, which may have increased its exposure to vortices in the area, resulting in a stronger response in middle fin as reflected in the plot. Debris or logs were timely cleared during the visual inspection. Following this removal, the middle fin possibly shifted back to its original position, allowing for accurate response recording in subsequent events.

4 Discussions

This section discussed about the challenges faced during testing faced by the prototype which provide valuable insights during deployment of FOSS. FOSS was deployed on 19th February 2023 and the data logging process was started.

There were some unforeseen complication with the site computer and data for the first month was not recovered. A new computer was installed on 18 October 2023 and data was successfully captured from 18-31 October, 2023, indicating that the sensor was functioning correctly. The data before 18th October was not recorded as the computer being replaced; however the during this period, FOSS was exposed to the environment.

Preliminary results of the sensor showcase a correlation with river gauging station flow data and rainfall data. Although high river data does not represent scouring at a structure, during storm Babet the response of the sensor decreased immediately and returned to normal level as the flow reduced. The response increased as the second storm (Ciara) approached.

During the two storm events, the ground condition were mostly saturated from the previous rainfall. In various locations in Northern Ireland, several rivers burst their banks which causes flooding at several locations along with the test site considered in this study. This flooding causes partial submergence of the green cabinet at the test site. Later the cabinet was checked and it was found that the isolator switch for the power supply remained unaffected. Also, the equipment stored in the above cabinet was located above the maximum water level remained unaffected. The responses were stored successfully even during the heavy floods which indicates that the sensor was operational.

The initially chosen sampling rate of 1000 Hz was relatively high, as it was uncertain whether scour would take place during the testing period. This high rate led to the generation of large size data, demanding significant storage capacity, which can be costly. Therefore, the sampling rate was lowered to 1 Hz. It was observed that this reduced rate remained effective while significantly minimizing file sizes, making it more practical for long-term bridge monitoring.

5 Conclusions

The aim of this work is to present the prototype FOSS and to assess whether this sensor could track the scour process in real-time before, during and after flooding events.

The chosen site for deployment of FOSS was proved to be appropriate, since it was convenient for visually inspecting the sensor and was not subjected to any additional vandalism. For two major storm events, scour is recorded through the sensor during its testing. Though the sensor is installed in an original scour hole that is artificially infilled, it was unexpected that this material would wash out again in a single flood events. The sensor physically survived storm plus scouring events since its installation. Also it is shown that using a 1 Hz rate would dramatically reduce the file size for long term monitoring of bridge network.

Several modifications could improve the response of the sensor, such as the height of the entire setup can be increased to measure greater scour depth. A better method of embedding the FBGs with a single rubber can also be investigated. Finally, FOSS could be connected to an online dashboard using data sim, for serving the bridge managers.

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