The development of a Fibre Bragg Grating river scour sensor utilizing vortex flow

K.E.J. Campbell
Principal Engineer, Department for Infrastructure (DfI), Belfast, Northern Ireland

Dr C. O'Higgins, Prof S.E. Taylor & Prof. G. Hamill
Queens University Belfast (QUB), Belfast, Northern Ireland

Dr M. Lydon,
University of Galway, Galway, Ireland

Prof A. O'Connor
Trinity College Dublin (TCD), Dublin, Ireland

Remco Nieuwland
Somni Solutions Ltd

ABSTRACT: The ability to effectively manage the deterioration of a network wide bridge stock condition from year on year is vital for the effective use of finite resources while maintaining public safety. The leading cause of bridge failure and deterioration globally is as a result of scouring. This research looks at the development of a Fibre Bragg Grating (FBG) scour sensor utilizing vortex flow effects, which can inform decision making within an existing road bridge management system (BMS). This paper will briefly review the current types of scour sensors available before outlining the initial development of a novel FBG sensor setup and associated prototype development. The findings of initial field trails are presented before outlining future research opportunities on the concept of incorporating real time data from targeted representative structures with on-site sensors to inform and update the scour risk rating.

1. INTRODUCTIONS

The issue of scouring of bridges and other structural assets subject to flowing water leading to structural failures is well documented and cited in numerous publications across the globe. Scour has been well established as the leading cause of bridge failure and deterioration in the United States, UK and worldwide (Shahriar et al., 2021)(Pizarro et al., 2020). As such, the study of scouring, its effects, monitoring and prevention is an active area of research and will continue to be so well into the future.

This paper will present a brief introduction into the types of scour, current monitoring devices before setting out the development of a novel scour monitoring device using Fibre Bragg Grating (FBG) sensors then detail future field trials and research.

1.1. NI Bridges

In Northern Ireland(NI), the Department for Infrastructure (DfI) encompasses the role of local Roads Authority and controls and maintains approximately 6978 bridges across the whole of NI (Stevens et al., 2020). These bridges are subject to regular inspections in order to accesses the overall condition of the structures and identifying any maintenance needs. Maintenance work is prioritised based on a range of factors, including the overall condition, public safety, engineering judgement, budgetary considerations and other competing priorities such as access agreements and environmental considerations.

These bridges vary greatly in their function, construction type, age and physical geometry. Over 53% are classified as masonry arch, 12% reinforced concrete pipe, 10% reinforced concrete slab, 7% concrete box culvert and 6% concrete beam (Stevens et al., 2020). The rest consist of various steel structures, composite concrete with steel and timber structures.

1.2. NI Masonry Arch Bridges

In NI, of the Masonry Arch (MA) bridges controlled by DfI, 94% carry roads over rivers and a further 2% are bridges over other watercourses. Of these bridges 95% are single span of which almost half are spanning approximately 1-3 meters. Around 99% are estimated as being over 100 years old, although this figure is difficult to verify as accurate records for the date of construction are not present in most NI bridge records with only an indicative year being assigned in the absence of an accurate date.

A review of the bridge files held by DfI also indicates that the majority have limited construction information on the structure. The majority do not have any detailed as-built drawings or any indication of the foundation depth, type (spread, piled or other) nor what the bridges are founded on (bedrock, clay, sand and gravel or other).

This lack of detail leads to a conservative approach by DfI bridge inspectors in relation to scour. Potential scouring, if identified during an inspection, results in the structure being flagged and its maintenance priority considered. A decision as to whether to opt for increased monitoring, further investigations or remedial works is taken. Often an assessment is based largely on engineering judgement to determine the severity of the scour on the overall bridge condition.

2. SCOUR MONITORING

2.1. Types of Scour

The Manual on scour at bridges C742 states that structures built in rivers and other channels can be vulnerable to scour around their foundations (Kirby et al., 2015). This manual covers in detail the various types of scour and scour processes extensively. For the purposes of this paper, a high-level brief outline will be included to provide a background for the sensor development presented later in this paper.

Most scouring can be classified into four main types: Natural, Contraction, Local and Total scour. All these scour effects are governed by a myriad of factors, which can continuously change in the natural river environment, it is not currently possible to accurately predict the exact extent and severity of scour at a particular structure at a given time or location. It is therefore necessary to try and manage this uncertainty by a range of means.

Visual inspections by trained bridge inspectors remain the primary approach taken by DfI for identifying and assessing scour at a bridge. This method is normally only conducted following a scour event when the floodwater recedes, and it is safe for inspectors to enter the river. This poses a problem for inspectors due to the potential for infilling masking the true extent. It is important to gain an understanding of the maximum scour in order to fully appreciate the risk that structure is under or to allow proactive actions to be taken. Risk based models and remote monitoring has attempted to bridge this gap for asset owners to supplement physical visual inspections.

2.2. Current Methods

Research indicates that the issue of monitoring and reporting scour accurately is a very difficult thing to quantify. None of the methods currently offer a panacea for the problem faced by asset owners. Factors affecting deployment include issues with regards cost, durability, performance and reliability.

Devices that record maximum scour such as float out devices and magnetic sliding collar devices provide limited detail on the progression of the scour or subsequent infilling. These devices tend to provide an indication that scouring has occurred to a discrete depth and do not account for infilling. These devices can be compromised by debris preventing them from working as intended thus giving the impression that scouring is not as severe Figure 1.

Float-Out devices have a couple of challenges that limit their longer-term effectiveness. These devices rely on batteries powering a wireless signal to a receiver when activated. These batteries eventually expire, and it is not typically possible to check they are functioning once installed. Indeed, a faulty device could become dislodged and subsequent infilling hide the event without any triggers being raised. Debris can also prevent these devices from floating out or sending a signal to the receiver Figure 1. Thus, again potentially giving you false readings.

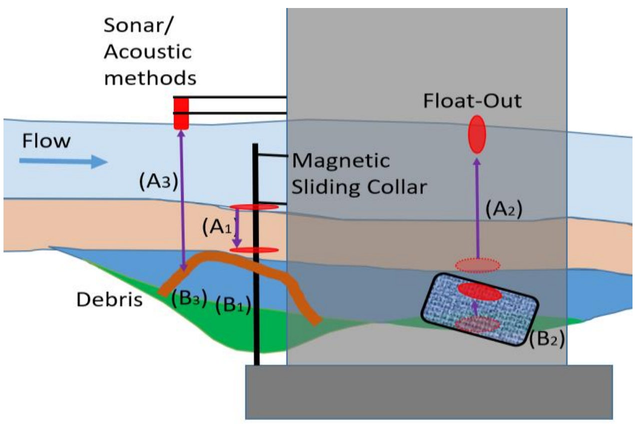

Figure 1 - Magnetic Sliding Collar, tracking the initial stages of scour (A1), further scouring (B1). Float-Out device, (A2). Debris (B2). Acoustic devices (A3), Debris (B3). (Fitzgerald, 2018)

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 easy to install, they do pose the challenge of often being expensive to purchase and maintain. Acoustic devices are relatively easy to install however can be susceptible to water borne debris giving non-representative measurements to bed level Figure 1. While others are limited to, freshwater environments or areas free of metallic debris.

Indirect methods of scour monitoring using sensors or vision-based computer methods to detect changes in the structural response (Fitzgerald et al., 2020). These types require a greater understanding of the likely structural response of each structure to scouring.

The main weakness of these methods are that they record the effects of scouring once it is having an appreciable impact on the structural performance rather than identifying/ warning the bridge owner of the potential for damaging scour in advance of it occurring. Therefore, these methods are not always suitable for a proactive approach to scour management.

3. FBG SENSOR DEVELOPMENT

3.1. Vortex Flow and current uses

When an object obstructs a flow, this results in vortices forming around that object. 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).

When a 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). These vortex-induced vibrations (VIV) are proportional to the flow velocity therefore within a pipe of known characteristics a determination of the flow can be based on these VIV (Cheng et al., 2011).

3.2. Application to scour measurement

Vortex flow sensors used in the oil and gas sector, measure flow accurately in pipelines. One such method consists of a bluff body placed in the pipe with a sensor probe that vibrates back and forth due to the vortex shedding down flow. The flow within the pipe is calculated using the frequency of these oscillations.

In a similar fashion, an alternative approach consists of a fin applied to the rear of the bluff body which moves with the frequency of the vortex shedding. FBG sensors in the fin record changes in strain and this is converted to give a flow (Cheng et al., 2011).

In natural rivers with open channel flow the ability to translate the VIV into a quantifiable measurement of flow is a much greater challenge and will not be discussed in this paper. The ability to pick up VIV presence can be utilised to give a binary 'Flow', 'No Flow' indicator which can be used for scour identification.

Sensors exposed to flowing water will vibrate and therefore register a signal whereas sensors buried would not vibrate beyond ambient values. If these sensors are buried at known depths relative to the bridge supports, it is possible to indicate the depth of scour at that location.

3.3. Initial trails

The basic principle explored in this sensor can be readily seen by the movement displayed by plant growth within a flowing river. The waving motion induced by river flow is akin to a flag fluttering in the wind.

In order to investigate whether VIV would translate to open channel flow; an initial experiment was set up to record this effect. The first step undertaken was to construct a rudimentary flume in order to test the principal under unpredictable conditions. This flume had uneven surfaces and was readily adaptable by placing bricks and debris to generate unpredictable flow conditions.

Figure 2 - Flume tank and red string tests

This set up was selected to enable the inclusion of debris, vegetation, gravel and bricks to investigate the effects in an un-calibrated flow. As this initial test was to check the viability of the system for river use it was deemed appropriate to use this rudimentary flume for these tests.

As the capacity of the available pump produced, a low flow rate in the flume a lightweight indicator was required to ensure motion could be visually detected initially. A length of red cord attached to a cylindrical rod was placed into the flume Figure 2. Motion was noted in the cord and without significant debris being introduced oscillated back and forth. Bricks were then added to the sides of the flume which constrained the flow and caused an increased movement in the cord.

The next stage was to investigate the effects of various profiles acting as the bluff body Figure 3, and observe the effects on the red cord. This red cord was then replaced by a thin piece of black rubber.

Although all shapes tested induced movement in the string and rubber, those with a flat face perpendicular to the flow displayed more movement. Objects which were offset to one side of the string, displayed greater movement again.

Having tested the basic principal, the next stage was to investigate suitable materials and fin profiles.

Initially a thin metal fin was considered, akin to sensors used in the oil and gas sector however this was quickly ruled out on durability grounds. Metal fins exposed to a natural marine/ aquatic environment are likely to be subjected to fouling, debris damage and corrosion. Consideration was given to coating these metal fins in a protective rubber coating but again durability concerns were raised. In order to simplify this approach a flexible fin with an embedded FBG sensor was proposed for the test sensor.

The next stage was to investigate bluff body profiles and the fin arrangements. The initial tests consisted of dummy prototypes of various profiles and a standard rectangular fin arrangement. These ranged from rectangular, circular, angular and offset. These tests showed that in river flow all prototypes exhibited movement with a range of flow conditions. Profiles with flat faces perpendicular to the oncoming flow caused more movement than those with rounded or streamlined profiles Figure 3. The prototypes were placed in various locations within a river site with varying flow characteristics. In areas of minimal flow the fins displayed movement and as the flow rate increased the rhythmical movement of the fins increased.

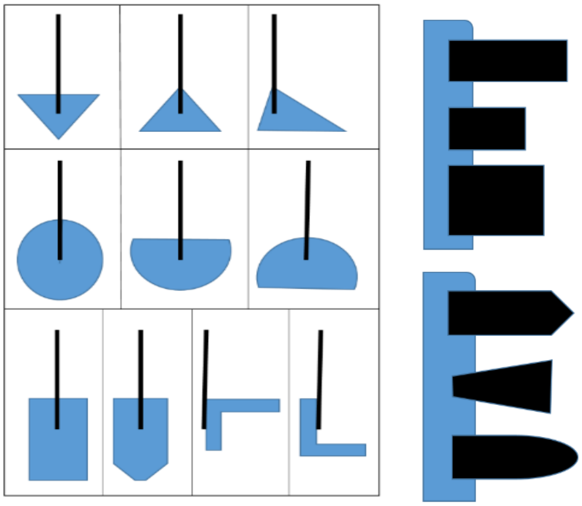

Figure 3 - Various bluff body profiles viewed in plan and various fin profiles viewed side on, used in the initial tests

The next phase explored the effects of the fin shape on the movement. Initially rectangular fins were tested with varying lengths and widths considered. Longer narrower fins moved more readily in flow Figure 4.

Figure 4 - River fin test

Variations on the fin shape where also tested with the 'fish tale' style fin that has a narrow width at the support and widens as it extends out, being the most responsive to the flow conditions Figure 3.

These tests concluded that although other shapes provided greater response to flow the regular rectangular fin can move in a range of flow conditions with no special alterations needed.

3.4. FBG fin lab tests

(Chan et al., 2006) describe the background and principal of FBG sensors in detail however for the purposes of this paper a brief summary is included as background. The basic concept is that a known input spectrum of light is transmitted through the Fibre Optic Cable (FOC). This FOC has a number of fibre Bragg gratings of known spacing that reflect a specified proportion of the input spectrum. When the FOC moves, this results in a slight shift in the spacing and therefore a change in the reflected spectrum is detected.

Initial trials utilised a FBG bonded to a 2mm 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.

In order to limit the potential for excessive bending or impact damage to the FOC/FBG sensors it was necessary to establish the minimum protrusion of the sensors and bend radius.

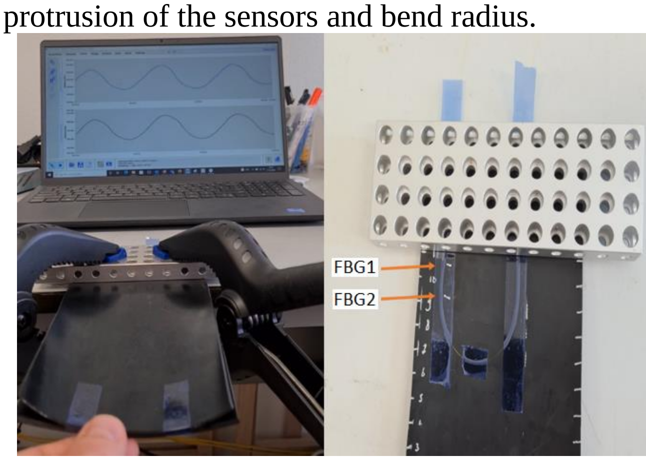

Figure 5 - FOC/ FBG lab protrusion test

A fin with a FBG sensor was clamped to the edge of a table and manually moved back and forth simulating movement. The FBG bonded to the fin measures the change in the strain at that point in the fin as it moves and translates this into a measurable response on the computer display Figure 5.

The next stage was to adjust the position of the clamps in order to establish the shortest distance the FBG sensor needed to project from the clamped edge in order to register a response. This further informed the refinment of the desgn of the prototype.

Knowing the minimum bend radius of the FBG cable and the minimum projection needed, this informed the size required for the rubber fins as well as the profiles used in the prototype.

In order to further protect the sensors, two curved sections where provided within the permitted bend radius of the FBG. The curved detailing on the profile permits the rubber fin to bend over this profile while preventing it from being bent excessively or crushed which would damage the FBG. This has the effect of providing a level of protection to the sensor from impact and damage from excessive bending.

A ‘dummy’ prototype was fabricated, to scale, to test all the assumptions made on the earlier trials. This test was conducted in a river environment at various points and video footage recorded of the movement of the fin Figure 6. Debris was introduced including floating vegetation and branches and the tests showed that the fin continued to move.

Figure 6 - 'Dummy' prototype river test

This test confirmed the assumptions and informed a refinement of the fabrication detailed drawings.

4. PLANNED FIELD TRAILS

4.1. Prototype development

Having established the basic layout of the sensor the next stage was to devise a way to test the effectiveness. To access the prototypes ability to track the progress of scour an arrangement of three sensors was considered. This configuration would allow for the scenarios of all sensors buried, one exposed two buried, three exposed and none buried and scenarios of partially buried fins. This would allow for the tracking of a scour and infilling event during our trails. Detailed fabrication drawing were developed and two operational prototypes were fabricated by Somni Technologies Lt Denmark and shipped to N.Ireland Figure 7. This consisted of stainless steel hollow sections welded and bolted together with FBGs bonded to rubber fins. One sensor was to be tested in a river enironment while the other in Lab conditions.

Figure 7 - Two functional prototypes

These prototypes where connected to a Micron Optics Optical Sensing Interrogator sm130 and the fins manually agitated back and forth to check the fins registered a response to movement Figure 8.

Figure 8 - Equipment setup

Then a simulated scouring test was undertaken whereby the top fin was moved back and forth and the traces observed. Then both the top and middle fin was moved to simulate the bed scouring down Figure 9 - Sensor trace showing top two fins registering movement.. Then all three fins moving was checked before reversing the procedure to represent infilling. The fins where also subjected to blunt impacts simulating floating debris impacts. These tests where in advance of deploying to a river or flume environment.

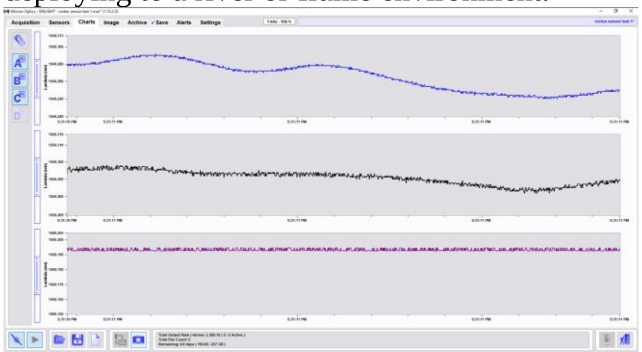

Figure 9 - Sensor trace showing top two fins registering movement.

4.2. Test site

A test site within a private garden beside the River Bann in Lawrencetown, Northern Ireland was selected with good access to the river, in a semi-rural location with convenient access to a mains power supply. One of the prototypes was fixed to a steel base plate and placed onto the riverbed in a relatively shallow part of the river Figure 10.

Figure 10 - Prototype river test

This demonstrated that in relatively low flow conditions a discernible trace was recorded from each fin sensor. When boards were used to funnel and constrict the flow towards the sensors the trace varied more indicating greater movement in the fins, and this was clearly visible on the fins. Having established this the next stage was to find a natural depression in the riverbed and move rocks to simulate a bridge pier. Natural riverbed material from the riverbanks was moved less than 10m from the test site and deposited around the sensor. This had the effect of burying the bottom fin. This translated to the trace for this fin levelling out, Figure 11 and in effect indicating that the fin was no longer moving and therefore buried.

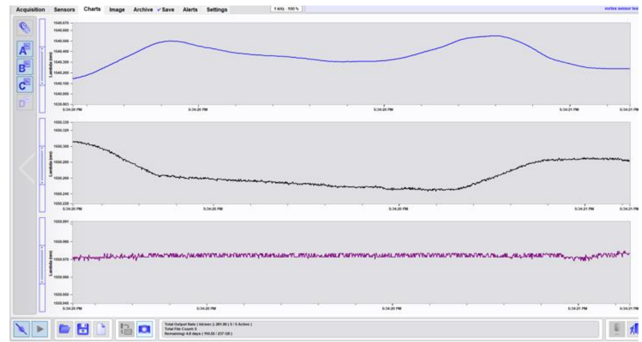

Figure 11 - Senor trace when bottom fin buried in river test

This was a very basic test but proved the concept of this sensor. Attempts to bury the next two fins proved difficult due to the flow in the river washing the material away before it could be fully buried. A temporary barrier was constructed around the sensor in order to build up the infilling around the sensor and then released to wash away the material. The material around the bottom fin was then allowed to wash away and once again this registered on the trace indicating movement in the fin.

This quick test proved the concept of the sensor however posed additional questions as to how to link the traces to the movements in the fins.

5. FUTURE REASEARCH POTENTIAL

Having established the basic concept works in these initial limited site trials the next stage is to set up a longer-term site trial on a bridge structure. A test site with a known history of scouring has been selected and steps are underway to instrument it this year. Although this site has evidence and history of scour, it is not possible to guarantee that the sensor will experience scouring during the testing phase. Supplementary testing using a fabricated controlled test rig to be deployed in a river, not presented in this paper, will be used to record simulated scouring and infilling events. This will ensure the concept of recording scour and infilling is explored during the testing phase. It is acknowledged by the authors that this test set up does not represent a realistic analogy of a real-world installation but was deemed appropriate for this stage of the sensor's development.

Another avenue of research is looking at the potential of incorporating real time data from targeted representative structures with on-site sensors to inform and update the scour risk rating of that asset.

6. CONCLUSIONS

The issue of scouring of bridge structures is a complex but important area of study. This paper has presented the initial work into the development of a novel real time scour monitoring sensor using FBG sensors. Initial trails have shown the concept of rubber fins embedded with FBGs has potential applications in this area. Further work is needed to refine the prototype sensor and deploy to a bridge site for a prolonged period. This prototype sensor has been registered with the UK patent office in 2022.

7. ACKNOWLEDGEMENTS

The authors would like to thank the Department for Infrastructure (DfI) for access to 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.

8. PREFERENCES

Chan, T. H. T., Yu, L., Tam, H. Y., Ni, Y. Q., Liu, S. Y., Chung, W. H., & Cheng, L. K. (2006). Fiber Bragg grating sensors for structural health monitoring of Tsing Ma bridge: Background and experimental observation. *Engineering Structures*, *28*(5), 648–659. https://doi.org/10.1016/J.ENGSTRUCT.2005.09.018

Cheng, L. K., Schiferli, W., Nieuwland, R. A., Franzen, A., den Boer, J. J., & Jansen, T. H. (2011). Development of a FBG vortex flow sensor for high-temperature applications. *21st International Conference on Optical Fiber Sensors*, *7753*(November 2018), 77536V. https://doi.org/10.1117/12.886051

Fitzgerald, P. C., OBrien, E. J., Malekjafarian, A., & Prendergas, L. J. (2020). *Acceleration-based Bridge Scour Monitoring*. *June*, 220–226. https://doi.org/10.3850/978-981-11-2723-6_24-cd

Kirby, A. M., Roca, M., Kitchen, A., Escarameia, M., & Chesterto, O. J. (2015). *Manual on Scour at Bridges and Other Hydraulic Structures - Second Edition*.

Pizarro, A., Manfreda, S., & Tubaldi, E. (2020). The science behind scour at bridge foundations: A review. *Water (Switzerland)*, *12*(2). https://doi.org/10.3390/w12020374

Shahriar, A. R., Montoya, B. M., Ortiz, A. C., & Gabr, M. A. (2021). Quantifying probability of deceedance estimates of clear water local scour around bridge piers. *Journal of Hydrology*, *597*, 126177. https://doi.org/10.1016/J.JHYDROL.2021.126177

Stevens, N.-A., Lydon, M., Campbell, K., Neeson, T., Marshall, A. H., & Taylor, S. E. (2020). Conversion of legacy inspection data to Bridge Condition Index (BCI) to establish baseline deterioration condition history for predictive maintenance models. *Civil Engineering Research in Ireland Conference Proceedings*.