Can Fiber-Optic Distributed Temperature Sensing Improve Bridge Scour Monitoring?

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ABSTRACT

Accurate predictions of maximum scour depths are of paramount importance for bridge crossing design and assessment. Despite major advances in our quantitative understanding of these phenomena, bridge failure due to hydraulically induced scour still represents a major technical, economical, and societal challenge. Fiber-optic distributed temperature sensing (FO-DTS) has the potential to enhance our ability to measure scour hole development. With high temporal and spatial resolutions, FO-DTS scour monitoring devices can dynamically locate and track the interface between the sediment and the water phases, providing new insights that in turn can improve the predictive capabilities of empirical and physics-based numerical methods. In this paper, the results of a series of laboratory flume experiments of a FO-DTS scour monitoring device that was constructed to monitor scour in the field are presented. Results indicated that the FO-DTS scour monitoring device was able to locate the aforementioned interface for various flow conditions, ranging from standing water to flow velocities of 2.8 cm/s. Moreover, when scour was mimicked by rapidly pulling the device out of the sediment bed, results indicated that the FO-DTS device was able to accurately track the rapid change in the location of the sediment-water interface. Finally, the potential of the FO-DTS scour monitoring device to advance our understanding of the spatial and temporal scales associated with scour phenomena is also discussed.

INTRODUCTION

Scour refers to the removal of channel-bed and/or streambank material due to the erosive action of flowing water (Arneson et al. 2012). In the case of bridge crossings, scour is generated by the reduction of the channel cross-sectional area as water flows under the bridge structure (or contraction scour) and by modifications to the flow field that are caused by the bridge foundations (or local scour). Accurate predictions of maximum scour depths are of paramount importance for bridge design and assessment. Such predictions are used to guide, for example, the selection of adequate foundation depths to guarantee that the bridge structures are not compromised during major flood events (Arneson et al. 2012).

Despite major advances in predicting scour phenomena, bridge failure due to hydraulically induced scour still represents a major technical, economical, and societal challenge (e.g., Briaud et al. 1999). Approximately 60% of bridge failures that occurred from 1960 to 1990 in the USA were caused by scour-related issues, resulting in an average of $30 million of damage each year (Deng and Cai 2010). Likewise, the Bridge Scour Evaluation Program reported in 2011 that 4.7% or approximately 23,000 bridges in the USA are scour critical, implying these bridges are likely to fail when subjected to a major flood event (Arneson et al. 2012).

Most commonly used numerical methods have been shown to overpredict the amount of scour (Landers and Mueller 1996; Falcone and Stark 2016). Such an overprediction results in a safer design, but it is less cost effective due to expensive countermeasures. One reason for the observed inaccuracies is the challenges associated with continuous monitoring of scour, particularly during flood events (Deng and Cai 2010). In most cases, scour data are collected immediately after, only capturing net amounts of scour caused by erosional and depositional processes during the passage of the event. Techniques for continuous monitoring of scour also exists, although their implementation is limited by deployments cost, debris-filled floods, and deployment difficulties (Manzoni et al. 2011). Field instrumentation that has been used for single and continuous scour monitoring include but are not limited to radar, sonar, scour chains, magnetic sliding collars, piezoelectric probes, heat dissipation gauges, photo-electric cells, conductance probes, time-domain reflectometry, fiber Bragg grating sensors, and thermal scour-deposition chains (e.g., Millard et al. 1998, Cooper et al. 2000, De Falco and Mele 2002, Nassif et al. 2002, Park et al. 2004, Hunt et al. 2005, Gariglio et al. 2013, Luce et al. 2013, Tonina et al. 2014, DeWeese et al. 2017).

Fiber-Optic Distributed Temperature Sensing (FO-DTS) provides a reliable technique to address the aforementioned challenges by enhancing our ability to monitor scour at high temporal and spatial resolutions. It has been reported that FO-DTS can record temperature changes every second and every 0.1 m for distances of up to 10,000 m (Cheng et al. 2017). Moreover, a temperature resolution as low as 0.1 °C can be achieved with proper calibration and long averaging time (Hausner et al. 2011). For scour monitoring, temperature is used as a tracer to reveal the location of the sediment-water interface, as flowing water and channel-bed sediment are expected to dissipate heat at different rates, thereby producing different thermal responses to heat perturbation along a FO-DTS sensor embedded in both materials. Manzoni et al. (2011) tested a similar approach to detect the sediment-water interface in laboratory experiments using the Fiber Bragg Gratings (FBG) technology. Although their results are promising, the employed FBG technology is practically restricted to 50 measurement points or less along a fiber optic sensing cable. The Raman-based FO-DTS technology – which is used herein – can significantly increase the number of measurement points, allowing for a finer resolution to be achieved over longer sensing distances. Therefore, scour monitoring devices based on FO-DTS have the potential to not only capture maximum scour depths, but also to provide new insights on the dynamic evolution of the scour holes during the passage of flood events.

The overarching objective of this work was to design a FO-DTS device capable of continuously monitoring scour in the field. In addition to providing key information regarding the bridge condition (e.g., structural stability during flood events), these data can be used to critically assess the performance of existing empirical (e.g., HEC-18 [Arneson et al. 2012]) and physics-based (e.g., SRH-2D [Lai 2008]) numerical methods that are commonly applied to examine scour phenomena at bridge crossings. This paper presents the results of a series of laboratory flume experiments that were intended to test the FO-DTS device's ability to locate and track the sediment-water interface for various flow conditions, ranging from standing water to flow velocities of 2.8 cm/s. Moreover, this paper also discusses the potential of the FO-DTS device to advance our quantitative and predictive understanding of scour phenomena at bridge crossings.

METHODS

A prototype of the FO-DTS scour monitoring device was constructed to test its ability to locate and track the sediment-water interface. The FO-DTS temperature measurement principles are based on quantifying – at two specific frequencies – the intensity of Raman based scattered light from which, in combination with the use of optical time domain reflectometry principles, temperatures can be determined at different positions along the optical fiber (Sayde et al., 2010). Herein, the employed FO-DTS sensor (0.9 mm OD, AFL ®) was tightly wrapped around the exterior of a 2-in PVC pipe. A resistive heating element composed of 20 AWG copper wire was wrapped on top of the FO-DTS sensing cable so that heat can be injected at constant rate along the cable. The thermal response was then recorded along the heated cable as function of the thermal properties of the material surrounding each particular section (i.e., sediment or water). Therefore, the recorded thermal response allowed us to differentiate when the surrounding material transitions from sediment to water (i.e., scour) and from water to sediment (i.e., deposition). The constructed prototype of the FO-DTS scour monitoring device, which had a diameter of 50.8 mm and a height of 0.6 m, is shown in Figure 1.

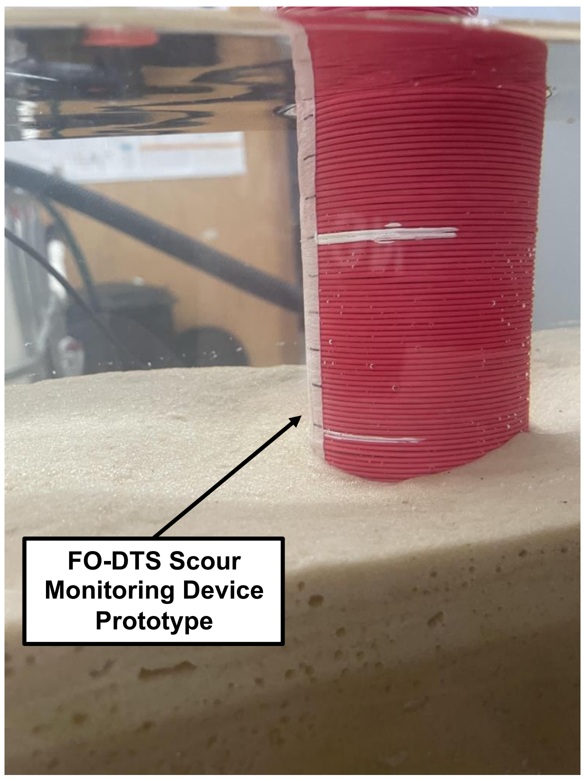

Figure 1 The constructed prototype of the FO-DTS scour monitoring device. The resistive heating element composed of 20 AWG copper wire that was wrapped on top of the FO-DTS sensing cable is shown in red.

A series of tests were conducted in a small laboratory flume housed in the Department of Biological and Agricultural Engineering at North Carolina State University (Figure 2). The flume is 2.4 m long, 0.2 m wide, and 0.6 m tall. For the tests, the flume was initially filled with sand up to a height of 0.3 m. The sand used for the channel-bed material was purified fine sand with a d_{50}

of 0.15 mm and silicon dioxide content greater than 99% (Glassil 530, Unimin Corporation-Marston, NC). The prototype was inserted vertically into the sand, so that half of it was either buried or submerged in water, whereas the other half was exposed to air (Figure 2). During the first tests, no scour was created, and the prototype was used to capture the static sediment-water interface at three different flow velocities. The average velocities were 2.8 cm/s (hereafter high flow), 0.6 cm/s (hereafter intermediate flow), and standing water (hereafter zero flow). In the subsequent tests, scour was simulated by rapidly pulling the prototype out of the sand channel-bed, exposing sections that were initially buried in sediment to water, thereby changing the recorded thermal response along the prototype. The latter tests were performed to track changes in the location of the sediment-water interface and to determine if these changes could be accurately captured. It should be noted that in the field, the exposure of initially buried sections of the prototype will be driven by sediment removal due to flowing water, which was not possible to recreate under the tested flow velocities.

Figure 2 Small laboratory flume housed in the Department of Biological and Agricultural Engineering at North Carolina State University. The prototype of the FO-DTS scour monitoring device is shown placed in the laboratory flume. Flow direction was from left to right.

RESULTS AND DISCUSSION

The FO-DTS instrument [Silixa XT-DTS™ (https://silixa.com/technology/xt-dts/)] used in the experiments produced an output of temperature versus distance along the FO sensing cable that had a sampling resolution of 0.25 m in space and 5 s in time. Figure 3 shows the normalized temperature increase along the heated reach of the cable installed around the prototype for the tested flow velocities. The temperatures were normalized by the temperature increase observed along a segment of the FO sensing cable that was buried in the sediment during the entire test. From vertical distance 0 mm to 210 mm, the prototype was buried in the sediment. The sediment-water interface was located at 210 mm. Then, from vertical distance 210 mm to 280 mm, the FO sensing cable was directly exposed to water. The remaining section of the cable was exposed to air above the water and thus heated up relatively quickly. Figure 3 shows that the section of the FO sensing cable that was submerged in water exhibited a lower thermal response to heating when compared to the section of the cable buried in the sand bed. This implies that the static sand-water interface can be effectively captured by examining the transition region between both thermal responses. Moreover, when examining the impact of the tested flow velocities on the thermal responses, the FO sensing cable submerged in water showed a lower thermal response for the high flow condition (i.e., more rapid cooling) and rather similar responses for the intermediate and zero flow conditions. The latter was probably caused by the relatively low flow velocity generated for the intermediate flow condition. More importantly, results indicated that the location of the water-sediment interface did not change over the evaluated range of flow velocities, as the thermal response of the FO sensing cable buried in the sediment remained practically unaltered.

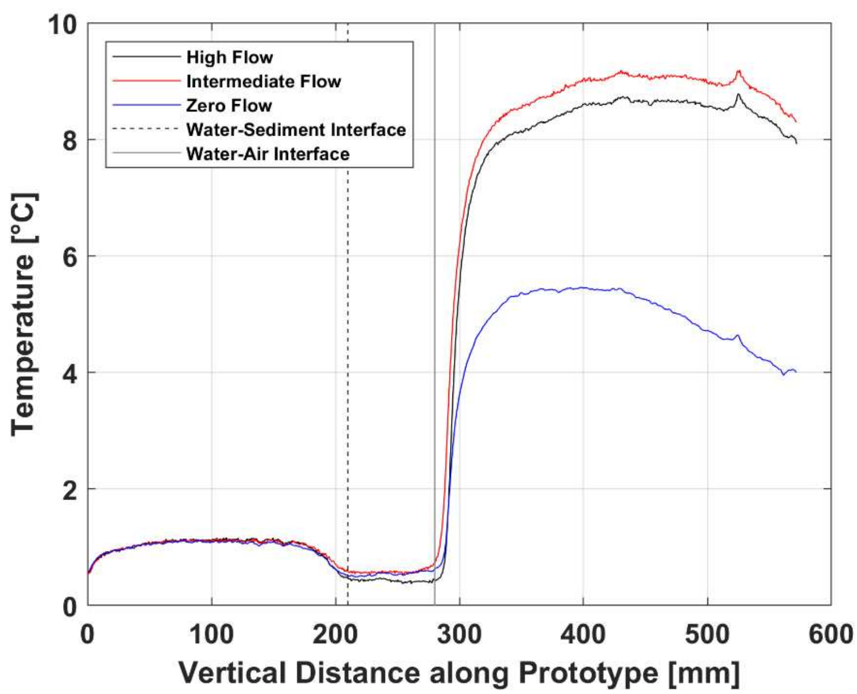

Figure 3 Average temperature variation along the FO sensing cable installed around the FO-DTS scour monitoring device for the tested flow conditions.

Similar results were observed in the scour-induced experiment. In this experiment, scour formation was generated by rapidly pulling the prototype out of the sand channel-bed to mimic exposing buried sections of the FO sensing cable to water when scour occurs. To recreate the formation of a scour depth equal to 5 cm, the prototype was pulled this distance away from the sand channel-bed surface. Figure 4 shows that the prototype was able to accurately track the change in the location of the sediment-water interface, which changed from vertical distance 210 mm (black arrow in Figure 4) to vertical distance 160 m (red arrow in Figure 4). Therefore, this implies that scour depths can be effectively measured by identifying changes in vertical distance along the prototype of the sediment-water interface.

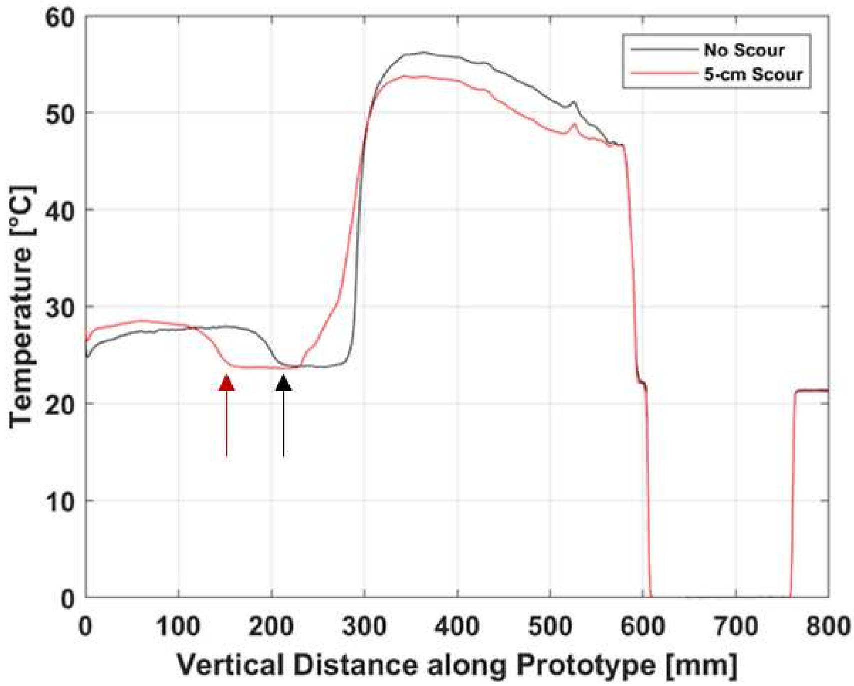

Figure 4 Temperature variation along the FO sensing cable installed around the FO-DTS scour monitoring device before and after scour was recreated. The location of the sediment-water interfaces for pre- and post-scour formation are shown with black and red arrows, respectively.

Implementing FO-DTS methods to monitor scour provides a number of advantages over currently used techniques. The most important one is that the FO-DTS system can be automated and deployed in the field for a prolonged period of time without any direct supervision. According to Fisher et al. (2013), for example, sonic fathometers are employed at most bridges in the U.S. to monitor scour. The sonic fathometer method requires the presence of a technician on site to supervise the operation of the device during data collection. Other autonomous devices to monitor scour formation exist, such as time-domain reflectometry. Nonetheless, these devices are typically not as durable as some FO sensing cables.

Furthermore, coupling FO-DTS measurements with higher dimensional numerical models (e.g., SHR-2D) is expected to render a more accurate representation of the hydro-morphodynamic processes that drive scour phenomena. Such a combination can allow us to understand event-based scour depths (i.e., a hydrologic regime approach) rather than relying in a single approach discharge for numerical predictions (e.g., for a given return period). The latter is fundamental not only to better understand river response to non-stationary water and sediment loading, but also to examine the reliance of design methods on historical flow conditions (Tullos et al., 2021).

CONCLUDING REMARKS

A series of laboratory flume experiments of a FO-DTS scour monitoring device that was constructed to monitor scour in the field were presented. The proposed FO-DTS scour monitoring device was able to, first, capture the sediment-water interface for varying flow velocities, and second, track changes in the location of this interface after a scour depth of 5 cm was mimicked.

Future work will focus on testing of additional prototype designs for the FO-DTS scour monitoring device, as well as on the deployment of the optimal design at a bridge crossing. Lastly, future work will also examine the coupling between higher dimensional models (e.g., SRH-2D) and data obtained from FO-DTS devices in the field to improve our quantitative and predictive understanding of event-based scour modeling and prediction.

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