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ABSTRACT

A new real time monitoring system for river bed elevation is presented. The instrument is based on optical fiber technology. With this device it is possible to reduce uncertainties in risk evaluations during flood events, especially those related to identification of bridges in critical scour condition. The working principle is explained and experimental tests are discussed. Device is presently ready for field application.

Introduction

Scour around bridge piers and abutments is one of the major causes for bridge failure (Richardson et al., 1993; Melville, 1992; Melville and Coleman, 2000). Real time monitoring of scour depths is a crucial tool to reduce uncertainties in evaluating risk at bridges during flood events. In spite of a relatively wide variety of possible technologies, no one can be considered to be a consolidated standard, as all methods (among them, echo sounders) present significant drawbacks, particularly during flood conditions (NCHRP, 1997).

The paper presents an innovative method to measure real-time scour depths around river bridge structures under both ordinary and flood conditions. The new approach (Cigada et al., 2008) adopts an array of temperature sensors based on optical fiber technology (Fiber Bragg Grating). Fiber is heated by an electrical circuit thanks to the Joule effect. This device measures temperature gradient to define in which environment every sensor is immersed; then it is possible determine the interface between water and sediments, that is the level of the river bed.

Presentation of the new device includes technical information about the instrument and the technology used. Moreover some laboratory tests are shown and discussed to evaluate the effectiveness and reliability of the technique.

Basic concepts of fiber Bragg grating

The fiber Bragg grating (FBG in the following) is a specific wavelength reflector (Hill et al., 1997) built up into the fiber core. More than one Bragg grating can be placed in the same fiber. The fiber is connected to sensing interrogation system that beams light within the fiber and receives reflected wavelengths. When light reaches the grating, a particular wavelength is reflected, while the others pass through it (Figure 1); the reflected wavelength depends on the geometrical features of the Bragg gratings (Hill et al., 1997). If in a fiber there is more than one Bragg grating, every FBG has a particular and different spectrum.

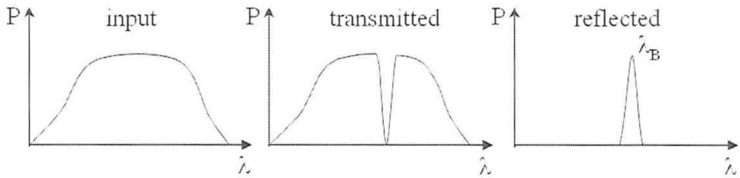

Figure 1. P is power, λ is the wavelength and λ_B is the reflected wavelength.

Literature (James et al., 1996) shows how the reflected wavelength shifts when the Bragg grating undergoes a mechanical strain and/or a temperature change (Figure 2), so that FBGs are commonly used for strain and temperature measurements.

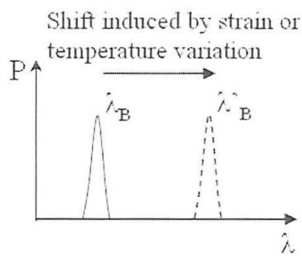

Figure 2. λ_B is the reflected wavelength at initial condition; λ'_B is the reflected wavelength after the shift.

The Bragg wavelength shift $\Delta\lambda$ due to a temperature change ΔT and a mechanical strain ε is:

$$\frac{\Delta\lambda}{\lambda_B} = k_g \cdot (\varepsilon_m + \varepsilon_t) + \alpha_r \cdot \Delta T = k_g \cdot (\varepsilon_m + \alpha_{sp} \cdot \Delta T) + \alpha_r \cdot \Delta T \qquad (1)$$

where λ_B is the Bragg wavelength at the starting condition, k_g is the gage factor and α_r is the change of the refraction index per unit of temperature. The first term on the right side describes the strain impact caused by force (ε_m) and temperature (ε_t), while the second term gives the effect of a temperature change on the refractive index of glass (glass constitutes the outer part of the fiber). Finally, the strain due to temperature variation can be expressed as $\varepsilon_t = \alpha_{sp}\ \Delta T$, where α_{sp} is the linear thermal expansion coefficient of the specimen.

For the present application, FBGs are used for solely temperature measurements. It is therefore necessary to make the response of each sensor non-dependent on possible mechanical strain of the fiber. In this case the fiber is embedded into a stainless steel tube (3 mm of diameter) abounded with thermal gel. Preliminary tests have proved that the FBG sensor, in this configuration, does not sense any mechanical strain ($\varepsilon_m = 0$). Equation (1) thus becomes:

$$\frac{\Delta\lambda}{\lambda_B} = \left(k_g \cdot \alpha_{sp} + \alpha_r\right) \cdot \Delta T \tag{2}$$

Once all the parameters of equation (2) are known, ΔT values are obtained by measurements of $\Delta\lambda$ along the fiber.

Device set up

The FBGs into a fiber measure temperature of the environment. This array is set up in vertical position, just close to the pier (Figure 3 shows system layout). In this configuration some sensors are exposed to flowing water and the rest of FBGs are buried in the bed.

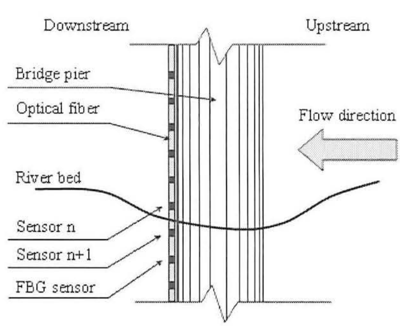

Figure 3. System layout.

Outside the steel tube that contains the fiber there is an electrical circuit connected to the power unit (Figure 4). When the power unit is turned on, the constant heat flux produced by the Joule effect is scattered due to conduction in the bed and convection in the flowing water. Heat dispersion is much higher in flowing water; therefore, the sensors exposed to flowing water sense a lower temperature increment than those buried in the bed when the electric circuit is switched on.

The measurement resolution depends on the distance between consecutive sensors. If one assumes that under ordinary conditions the bed level is defined by sensors n and n+1 (Figure 3), during a flood event the local scour around bridge pier changes the bed level and sensor n+1 (Figure 3) becomes exposed to flowing water. This changing decrease the different heat dispersion sensed by that FBG, which starts sensing a lower temperature increment respect to the previous condition. In this case the new bed level is defined by sensors n+1 and n+2. This measurement device can always determine the level of the river bottom, whatever flow conditions are considered.

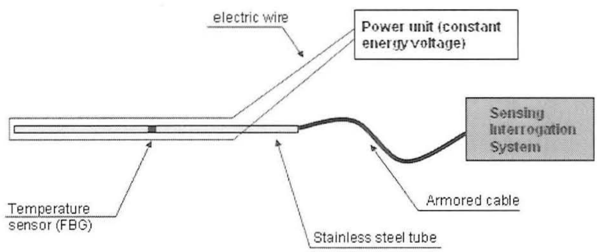

Figure 4. Electric wire configuration.

Figure 5 shows the final configuration for the laboratory scale device used in the tests. Three electric wires were wrapped along the steel tube. The contact between tube and electrical circuit is guarantee by heat-shrinking. Notice that a field-scale sensor would have the same dimensions.

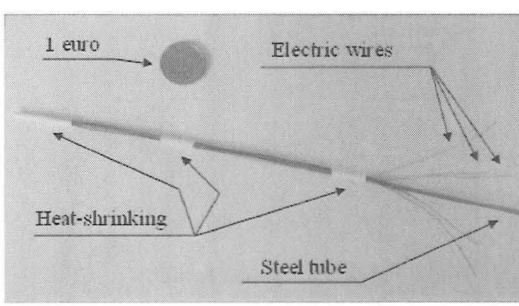

Figure 5. Main device components. In the final configuration the heat-shrinking covers the whole fiber.

Laboratory tests

The tests have been performed in the laboratory of Hydraulics at the Politecnico di Milano, Milan, Italy. The water channel had base and height of 100 and 70 cm, respectively. The water level was 60 cm and the average velocity of the flow was 0,4 m/s. The fiber was attached to a cylinder that simulated a pier. This layout allowed to test temperature sensors immersed in flowing water (Figure 6a).

To simulate the sensors buried in bed an external cylinder was added (with a larger diameter respect to the previous cylinder). The space between them was filled up with sediments and saturated with water (Figure 6b).

For both configurations the main characteristics of all tests are: dissipated power 0→50,5 W/m and data collected for longer than 100 seconds.

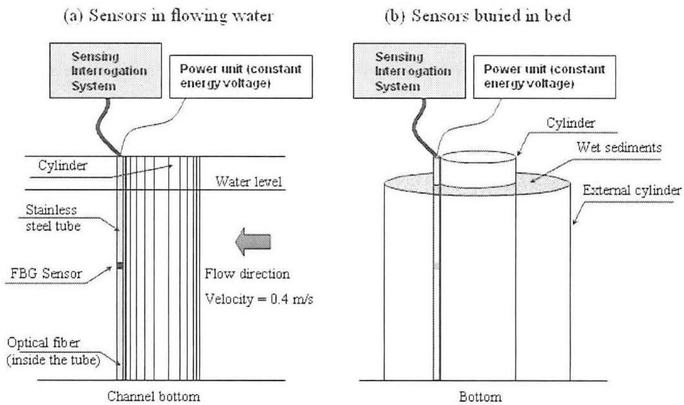

Figure 6. Layout of laboratory tests.

Figure 7 presents a typical response of the sensors in the two different environments: flowing water and buried in bed (wet sediments). Before t = 0 s, the power unit is off and the sensor measures the temperature of the environment. When the power unit is turned on, the measured temperature value increases. Heat is dissipated by conduction in the bed and convection in the flowing water. For both situations the response of the sensors shows an initial transient where the constant generated heat flux is higher than the flux scattered in the environment, and the temperature measured by the sensor increases. After the transitory, an approximately stable condition is reached.

The difference ΔT between the equilibrium and the initial temperature can be used to distinguish among sensors in different conditions (i.e., facing flowing fluid or saturated soil). The increase of (equilibrium) temperature due to heat dissipation, ΔT, is always larger in the soil than in the flowing water. However the power of heat generation highly influences the reliability of the measure. In fact an increase of dissipated power goes along with an increase of temperature variation (Figure 7). The relationship between the dissipated power and the temperature variation

(Δtemperature) is approximately linear for both the environments in which the sensor is immersed; in flowing water the proportionality coefficient is smaller than that for the soil. As a consequence, sensors exposed to the different environments can be distinguished in spite of the unavoidable local disturbances, given that the heating power is large enough. For the tested configuration, figure 8 shows that a dissipated power larger than 10-15W/m is sufficient to robustly detect the two different behaviours.

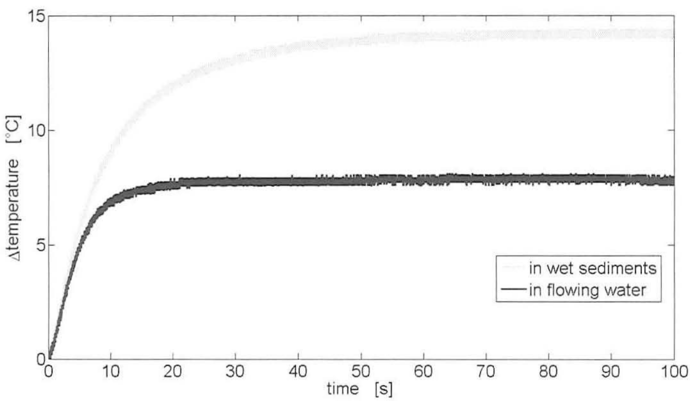

Figure 7. Response of the FBG in flowing water (black line) and in wet sediments (gray line). The constant dissipated power per meter of fiber was 50.5 W/m.

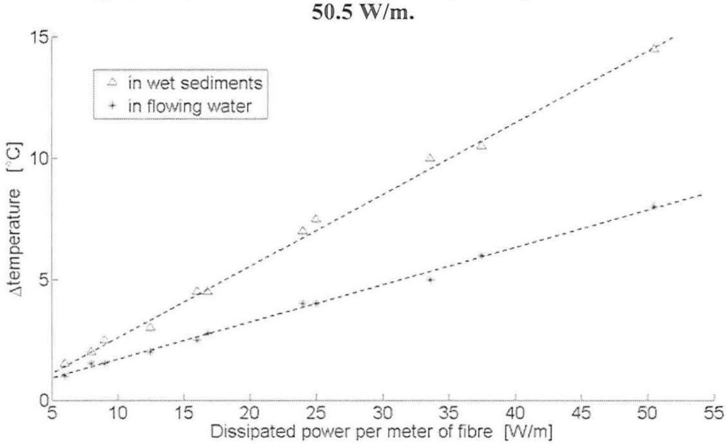

Figure 8. Δtemperature (steady state temperature – starting temperature) (ΔT in equation 1) as a function of the dissipated power in Watt per meter of fiber. The sensor is that already considered in Figure 7.

As an alternative to the temperature increase ΔT, proper time constant could be used to distinguish sensors immersed in the two environments. In fact, time histories for temperatures can be approximated as:

$$T = \Delta T\left(1 - e^{-T/\tau}\right) + TS \qquad (3)$$

where ΔT was already defined as the difference between the steady-state temperature and the starting temperature, TS is the starting temperature and τ is the time constant.

The response of sensors in the two environments is different in term of time constant. Figure 9 shows that time constants have little (if any) dependence on the dissipated power, being equal to about 10 seconds for wet sediments and about 5 seconds for flowing water condition.

The time constant of wet sediments is always higher than the flowing water condition for any dissipated power (Figure 10). This result allows to consider the time constant τ as an additional parameter. In fact it is possible define the bed level estimating the time constant for all the sensors.

The comparison between figures 8 and 9 clearly shows that the combined used of the time different ΔT and the time constant τ allow to discriminate between the two environments for any value of the dissipated power.

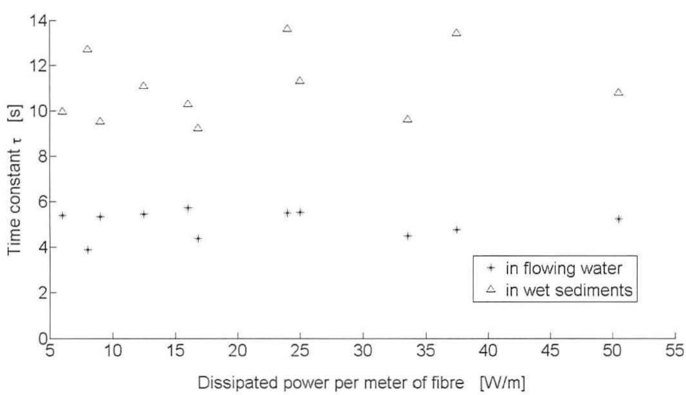

Figure 9. Time constant τ as a function of the dissipated power in Watt per meter of fiber.

Conclusion

In this work a device for scour measurement has been tested. The device is a sedimenter composed by an array of temperature sensors based on optical fiber technology (Bragg gratings). Fibers are heated by an electrical circuit and the sediment/water interface is detected by means of the different thermal behaviour of the system in two environments. Both the temperature increase due to the heating and time constant of transients can be used as indicators, as they are both larger for sensors buried in the bed than those for sensors in flowing water. The position of the bed is identified by two consecutive sensors showing different thermal behaviours. The combined use of both indicators allows for reliable detection of the bed level.

Laboratory tests have proved that the response of the instrument is satisfactory. The instrument can find out the bed level independently of flow condition of the river. Even if other tests are in progress to improve the instrument efficiency the first experimental installation will be ready in few months near Borgoforte, in the Po River, Italy.

Acknowledgements

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