Continuous Monitoring of Masonry Arch Bridges to Evaluate the Scour Action

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Abstract. The shallow foundations that often characterizes multi-span masonry arch bridges are highly vulnerable to the soil settlements typically induced by riverbed scouring. Consequently, monitoring of scouring effects is of paramount importance to ensure the safe operation of these river bridges. Within a recent collaboration between Politecnico di Milano and Regione Lombardia, a multi-span masonry arch bridge has been selected to exemplify a quasi-static monitoring strategy capable of detecting the flood-induced scour. The structure, built during the second half of the 19th century, was subjected to numerous strengthening interventions, especially on the pier foundations resting on the riverbed. The installed heterogeneous sensor network consists of tiltmeters (measuring the rotation of the piers at the skewback level), 1 weather station, 1 hydrometer, and 1 echo-sounder. In addition, the detection of debris accumulation is performed with cameras taking pictures of the piers from the upstream side.

After a concise description of the structure and the Sesia River, the paper focuses on the adopted measuring system and the results obtained in the first months of continuous monitoring.

Keywords: Masonry bridge · Scour action · Structural health monitoring · Static monitoring · Hydraulics

1 Introduction

Broadly speaking, scour is a soil-structure interaction problem that represents the most common cause of collapse for river bridges [1]. As shown by different authors [2, 3], multi-span masonry arch bridges are highly vulnerable to the scour-induced effects due to the shallow foundations in the riverbed and the high transverse stiffness. Consequently, the relatively low-cost monitoring of scouring effects is of paramount importance to ensure the safe operation of these river bridges.

The permanent monitoring strategies for the detection of scouring can be divided into two main groups: (a) the direct methods based on underwater instrumentations, measuring the riverbed variations, and (b) the indirect methods based on the measure

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of variations in a structural feature (e.g., the tilting of a pier). The former are usually local sensors – such as the echo-sounders – describing the depth of scour over time. The main disadvantage of these technologies are the costs associated to an installation at multiple positions, namely at the base of multiple piers. On the other hand, the structural sensors – such as the tiltmeters – are usually less expensive, so that the installation on multiple positions is easily implemented. Conversely, those sensors do not give direct information on the scour intensity. A review of scour monitoring techniques is reported in [4].

Within a recent joint research between Regione Lombardia and Politecnico di Milano, several bridges in the north of Italy were studied (see, e.g., [5–7]). The main objective of the project was the definition of criteria and guidelines for the maintenance and management of roadway infrastructures. Firstly, a risk-based prioritization methodology at a regional scale was adopted, and, subsequently, recommendations for the implementations of Structural Health Monitoring (SHM) strategies on different structural typologies were provided. Nine bridges were then selected for the validation and the practical application of the proposed approach.

The paper illustrates the application of the SHM strategy for multi-span masonry arch bridges subjected to scour actions on one of the selected structures: the *Candia* bridge (Fig. 1). The *Candia* bridge, crossing the Sesia River, is a masonry bridge built in the second half of the 19th century. The inspection on the structure revealed that all pier footings resting on the riverbed underwent strengthening interventions, highlighting the vulnerability to scour actions. Consequently, the permanent monitoring system was designed to investigate the flood-induced scour risk acquiring data from both the structure, the river, and the riverbed with a heterogeneous sensor network. The preliminary results show a promise toward the possibility to perform the early detection of scour-induced damages.

Fig. 1. The *Candia* bridge: view from the downstream of Sesia River.

2 Description of the Candia Bridge

The *Candia* bridge (Fig. 1) is an historical multi-span masonry arch bridge crossing the Sesia River in the neighborhood of the small town of Candia Lomellina. The structure is approximately 330 m long, and it is composed by 16 segmental arches (with span equal to 17 m), 15 piers, and end abutments. The deck width is equal to 10 m and includes a roadway and a railway track, with the latter being inactive since 2010. The documentary research revealed that the structure was conceivably built in 1869 during the construction of the railway line between Astiand Mortara [8].

Regarding the interaction with the Sesia River, the bridge crosses the river 5 km upstream of the confluence with Po River. Flow regime is rather torrential, with flow discharges ranging between 70 m^3/s and 5000 m^3/s. In case of a 200-year flood event, water can reach an elevation of about 105 mabove sea level (asl) and 1 m above the skewback of the bridge arches. Moreover, the river is close enough to the Po River as to feel its backwater effect. Consequently, different hydraulic scenarios may occur at the bridge section. In other words, multiple flow rates and velocities can correspond to a given water depth. The Sesia River has a meandering channel pattern, which appears planimetrically stable from aerial images observation since 1954. On the other hand, the river has showed bed elevation changes, inducing a scour process at the base of the pier footings. Scour can develop at different space and time scales. At large scales, the altimetric profile of Sesia River suffered a general degradation of several meters in the last century. In particular, along the period 1960–2000, the river generally eroded for 2–3 m. This process led to threat to the stability of the bridge pier foundations. For this reason, all pier footings resting on the riverbed underwent strengthening interventions (see, e.g., the piers in Fig. 1).

Armoring intervention of the riverbed were carried out on several occasions to stabilize the sediments around the foundations. To the authors' knowledge, the last intervention of riverbed stabilization was performed after 2003 around the most eroded piers at the left side of the channel, where flow concentrates in normal condition. This operation, however, simply modified the local morphology of the riverbed, deviating the main flux - and therefore the scour process - from the left to the central-channel piers. Figure 2 shows a representation of this mechanism. Scour can further develop locally during a single flood event, due to the local acceleration of the flow around the piers. The presence of debris, which easily accumulates in front of the piers during a flood event, can further intensify the local scour process.

Fig. 2. Satellite images of the Sesia River before and after the armoring intervention.

3 The Continuous Monitoring System

The foundation settlements induced by scouring has often an asymmetrical distribution, causing small rotations along the longitudinal and transversal axis of the bridge [2]. The onsite survey on the central piers of the *Candia* bridge revealed that the maximum difference in the riverbed level between the upstream and the downstream is about 3 m. Hence, rotational settlements in the transverse direction are more likely to occur. Consequently, the proposed quasi-static monitoring system is primarily based on the measurement of pier rotations. In addition, the environmental factors that may affect the structural response are measured as well.

The continuous monitoring system (Fig. 3) of the *Candia* bridge includes: (a) 15 MEMS tiltmeters; (b) 1 weather station; (c) 1 hydrometer; (d) 1 echo-sounder and (e) 2 cameras. The tiltmeters are installed at the skewback of the arches, measuring the traverse rotation of the piers. As shown in Fig. 3, the MEMS tiltmeters are placed only on the piers located in the riverbed.; furthermore, the piers that were most affected by the scour events since 2003 (Fig. 2) are monitored with two tiltmeters: one for each skewback. The weather station (measuring temperature, humidity, rainfall intensity, wind speed and wind direction) is installed at the deck level. At last, the hydraulic sensors (i.e., the hydrometer and the echo-sounder) measure the water level and the distance between a fixed point and the riverbed, respectively. In addition, the detection of debris accumulation is performed with 2 cameras taking pictures of the piers from the upstream side.

The continuous monitoring system has been active since November 22nd, 2020. The sensor network has a sampling frequency of 1 Hz with the only exception of the cameras that acquire pictures every 10 min. The recorded data are collected every hour in 1 binary file that is transmitted to Politecnico di Milano for the analysis. In the post-processing phase the recoded data are averaged to obtain a single observation every hour. It is worth mentioning that, due to echo-sounder malfunctioning, this sensor did not record any data so far and the substitution of the device has been scheduled.

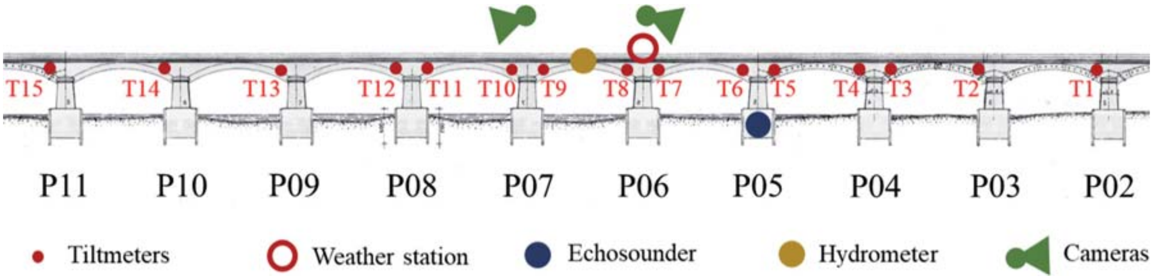

Fig. 3. General layout of the quasi-static monitoring system installed on the *Candia* bridge.

4 Data Analysis: Preliminary Results

This section summarises the main results of the quasi-static monitoring system for a period of more than 5 months, from 22/11/2020 to 01/05/2021. During this time period

3598 1-h dataset were collected and analysed. In addition, the upstream side pictures – taken with the permanent cameras in the daylight – were used to realise a time-laps video showing the evolution of debris accumulation. In Fig. 4 two images of the upstream side of the bridge are reported, showing the impressive debris accumulation on pier 5 after the last flooding in the beginning of October 2020.

Fig. 4. Pictures of the upstream side from the permanently installed cameras.

Regarding the measure of the environmental parameters, Fig. 5(a) presents the evolution of the river (water) level measured with the hydrometer in terms of elevation above the sea level (m asl). The inspection of Fig. 5(a) reveals that the water elevation changed about 1.5 m during the monitoring period. It is worth considering that during the expected 200-year event, water can reach an elevation of about 105 m also, namely, rising about 8 m from the minimum measured water level. Therefore, the detected variations in the water level are negligible in respect to the expected rare events and so that only negligible scour values should be expected under such conditions. To further confirm this assumption, the recorded pier rotations have no correlation with hydrometer measurements. Figure 5(b) illustrates the evolution of the outdoor temperature measured with the weather station installed on the bridge. The maximum and minimum recorded temperatures in the selected period are equal to 26 °C and −6 °C, respectively.

Figure 6 shows the time evolution of measured rotations of two selected piers (i.e., P4 and P6). It is worth mentioning that both piers are located in the area that – after 2003, see Fig. 2 – has been affected by scouring and, therefore are monitored with two tiltmeters each. The inspection of Figs. 5(b) and Fig. 6 firstly suggests that the fluctuations of the measured pier rotations follow the temperature variation. In order to further demonstrate the temperature dependence, Fig. 7 shows the correlation of the measured rotations at pier 4 and pier 6: all the selected pier rotations exhibit an almost linear correlation with temperature. The main difference between the tiltmeter measurements at piers 4 and piers 6 is a sharp permanent shift in the rotation-temperature relationship starting from the 31/03/2021. Particularly, the variation of the linear correlation is demonstrated by the changes in the R^2 coefficient (Table 1). The tiltmeters T3 and T4 (pier 4) exhibit a high value of R^2 – close to 0.9 – for the entire monitoring period. Conversely, the tiltmeters T7 and T8 (pier 6) exhibit a clear drop in R^2 coefficient after the 31/03/2021.

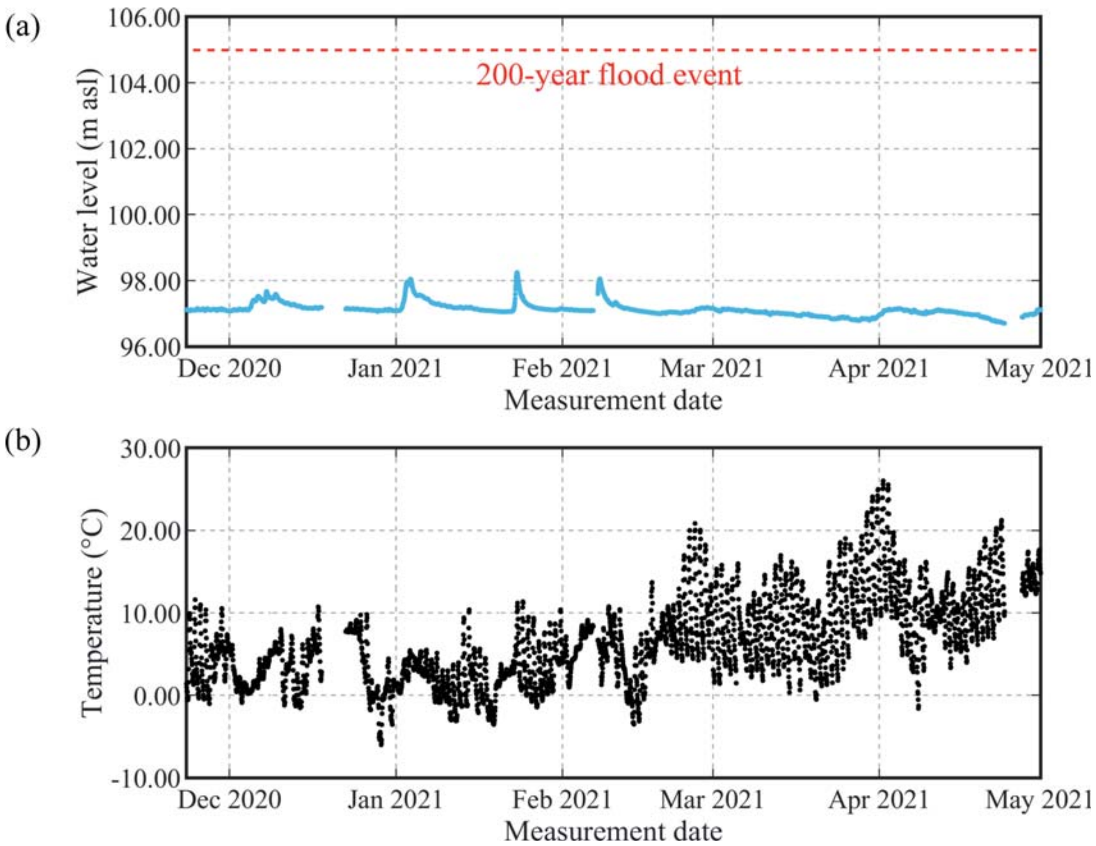

Fig. 5. Variation in time of measured water level (a) and temperature (b).

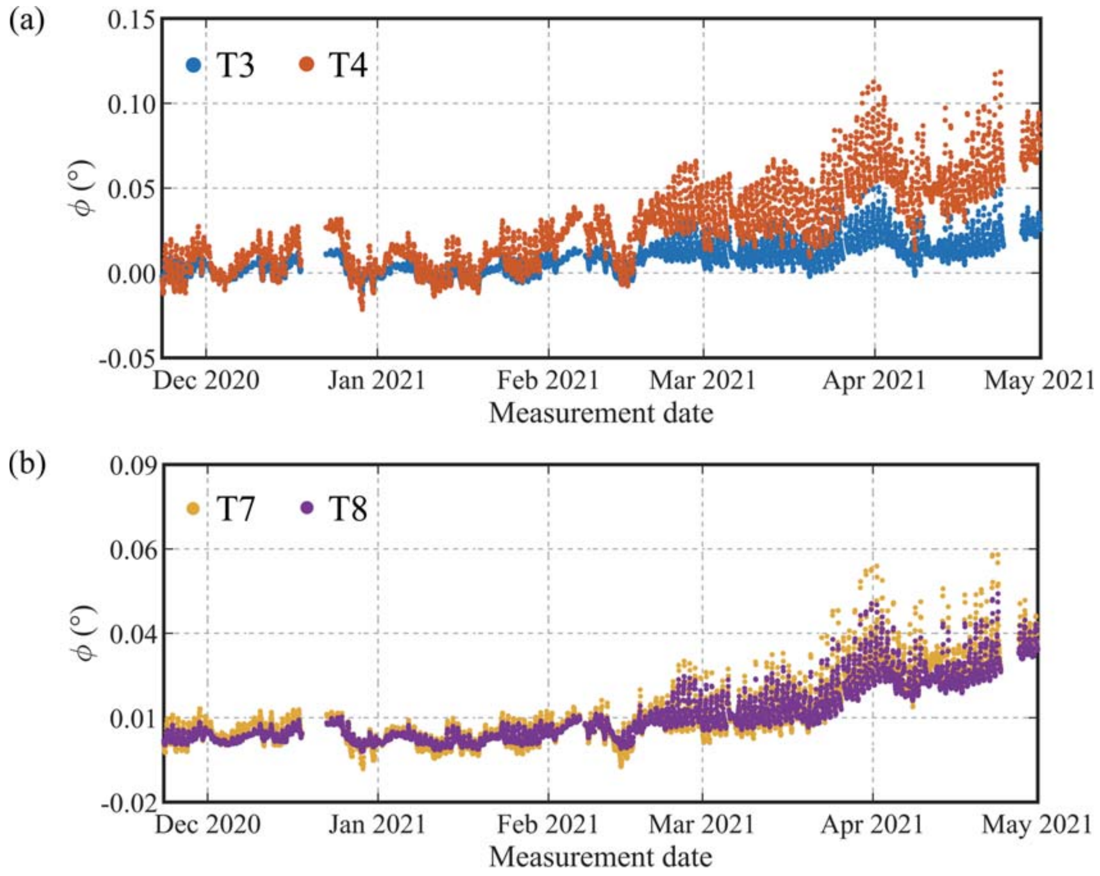

Fig. 6. Time variation of rotations: (a) tiltmeters T3 and T4 at pier 4, and (b) tiltmeters T7 and T8 at pier 6.

Table 1. Evolution in time of the R^2 coefficient measuring the rotation-temperature correlation.

Measurement period	R^2			
	T3	T4	T7	T8
22/11/2020 – 31/03/2021	0.93	0.88	0.84	0.81
22/11/2020 – 01/05/2021	0.89	0.90	0.73	0.74

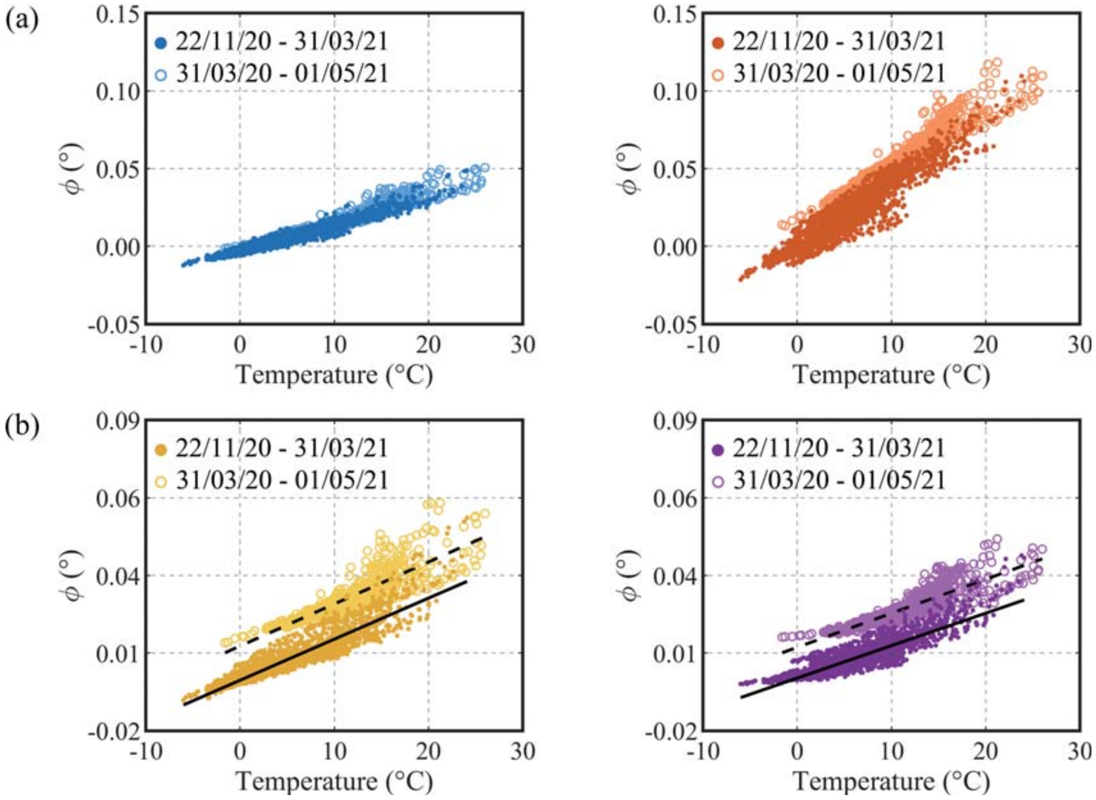

Fig. 7. Changes in the rotation-temperature correlation before and after the 31/03/2021: (a) tiltmeters T3 and T4 at pier 4, and (b) tiltmeters T7 and T8 at pier 6.

5 Conclusions and Future Developments

The paper illustrates the continuous monitoring system recently designed and installed on the historical masonry arch bridge of *Candia* over the Sesia River.

The main aim of the monitoring system is to detect the onset of structural damages induce by the scour action at the bridge foundations. Variations in the structural behavior of the bridge are measured with a series of MEMS tiltmeters installed on top of the bridge piers. In addition, a weather station was installed to assess the effect of the environmental parameters on the structural behavior of the bridge. To account for the hydraulic actions, and for the scour in particular, a hydrometer, an echo-sounder, and two cameras were installed. It is worth noting that relevant flood events – which would induce scour – did not occur during the first five months of recording.

From the analysis of the recorded data, the following conclusions can be drawn:

- The outdoor temperature is confirmed as the dominant driver for the tilt variations.
- The water elevation does not show any correlation with the pier rotations. However, the recorded water level variations – up to 1.5 m – are negligible in respect to the expected rare flood events.
- A slight permanent shift in the rotation-temperature relationship of the tiltmeters at pier 6 is detected since 31/03/2021. The physical phenomenon that caused this anomalous variation might reveal the onset of a structural damage and it should bee carefully

investigated by examining the data collected during a more extended monitoring period.

Within the next months, the complete SHM strategy will be implemented involving a data-driven approach to remove the effects of environmental factors from measured rotations, whereas the scour influence on the bridge will be conceivably detected from classic novelty analysis [9] of the tilt residual errors, as well as from echo-sounder measurements. This hybrid system may not prevent future damages of the structure [10]; however, it can be of crucial importance to address maintenance and repairing operations.

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