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# Real-Time Assessment of Bridge Vulnerability

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*A real time monitoring system has been installed on the road bridge over the River Po, in Borgoforte (Province of Mantova), Italy. A variety of sensors measures the basic environmental parameters in order to assess bridge stability with respect to flood scenarios (scouring and fluid-dynamic load); among them, two different technologies are used to detect the evolution of the river bed elevation close to the piers due to scour processes, namely, echo sounders and BLESS, an optical sedimeter recently developed and patented by Politecnico di Milano.*
*This paper discusses how registered data can be composed for dynamic assessment of the vulnerability of the structure. We could analyse data relative five months of working time for the monitoring system; in spite of the relative short duration of the test, some characteristics for the two systems and, more in general, for the whole monitoring station, are clearly. On the contrary, the test is too short to allow conclusions about one of the most critical issue for scour monitoring stations, that is, physical resistance to high stage events, which is potentially one of the main advantages of the BLESS sedimeter with respect to conventional alternative solutions. Results are discussed with respect to the use of the monitoring station as a support for decisions during emergencies.*

## Key words
Monitoring, optical fiber, bridge scour, risk management.

## I INTRODUCTION

Morphological variations of the river bed in correspondence of a bridge can significantly alter the geometrical and, therefore dynamic conditions of the structure; typically, river bed degradation due to local or diffuse scour decreases the stability of the foundation and increases the critical bending moments on the piers due to the increase of arms for active forces. It is well known that such morphological processes are not easy to predict in a deterministic sense: in spite of a large amount of studies on the subject, for instance [Oliveto and Hager, 2002] and [Ballio et al., 2010], engineers are indeed able to provide evaluations for maximum possible degradation levels, but in many cases such extreme values are not experienced by the structures; moreover, very little is known about the real time scales for scour evolution.

The high uncertainties described above can be compensated by structural measures such as foundations and piers over-dimensioning for bridges under construction or reinforcement of existing ones. However, this approach leads to increase of costs which, in many cases, appears as not justified by the experience. On the other side, it is well known that degradation of the bed around bridge piers or abutments is one of the main causes for river bridge failure [Melville and Coleman, 2000] and [HEC-23, 2009].

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Real-time monitoring systems are a possible alternative to structural countermeasures to increase bridge safety: typically, they do not mitigate the risk for the structure, but they allow the authority responsible for the bridge to verify the residual risk for the crossing and, therefore decide whether the bridge should be closed to traffic. Such systems should first of all be able to measure scour conditions, as they are a key issue for a punctual evaluation of bridge safety; however, bed levels alone do not provide all the necessary information for a risk assessment, as active loads due to wind, water and traffic change with environmental conditions, thus requiring dynamic measurement.

Scientific and technical literature provide several examples of permanent monitoring stations at river bridges: examples in [NCHRP, 1997], [Conaway, 2006], [NCHRP, 2009], and [Hunt, 2010]. Such experience, however, mainly focussed on scour around the structure, without considering the remaining boundary conditions. In this paper we present a recent experience of a more complete monitoring system recently installed on the Po river, Italy, where all relevant parameters for bridge safety are recorded, thus allowing for a real-time assessment of the conditions for the structure. Section II gives a brief overview of the site; the structural modelling of the bridge is described in Section III, which also presents results for the sensitivity of bridge resistance with respect to the control parameter for the system. Section IV describes the monitoring system installed on the bridge. The final section presents and discusses preliminary results from the initial data after installation.

## II BORGOFORTE BRIDGE

The bridge in Borgoforte (Province of Mantova) joins Mantova to Modena crossing river Po, the biggest Italian river. For normal flow conditions, the river bed is about 300 m wide at the bridge. Only four piers have permanently submerged foundations (Fig. 1a), the remaining ones are positioned on the flood plain. Piers in the main channel of the river contain two rows of circular piles (Fig. 2).


**Figure 1: (a) Plan of the bridge with pier numbering; (b) Borgoforte Bridge from upstream.**

After a flood in 2000, a bathymetric survey indicated the presence of a residual scour hole between the two central piers in the river (piers 31 and 32, Fig. 1), whose maximum depth was 15 meters; it is reasonable to assume that larger depths may have been reached during the flood event. After this event, piers from 31 to 33 were stabilized by adding four piles to each pier (Fig. 1b). No structural reinforcement was applied to pier 30, as it is situated close to the bank, where the bed level is higher. However, hydraulic modelling of the river reach indicates that, for high stage conditions, the flow tends to concentrate on the right bank; a real-time monitoring system was, therefore, installed to assess the risk for pier 30. The monitoring system has been in operation since June 2011.

## III STRUCTURAL ANALYSIS OF THE BRIDGE

Standard verification criteria for the bridge have been applied; the critical scenario refers to bending moment at the base of the piles. No details of the structural model will be given; only formal links between the main variables and the critical control parameters are discussed, in order to clarify the role of the monitoring system (Section IV) with respect to the evaluation of the risk for the structure. In the following, all loads will be referred to the portion of competence of a single pier and/or the corresponding section of the bridge deck.

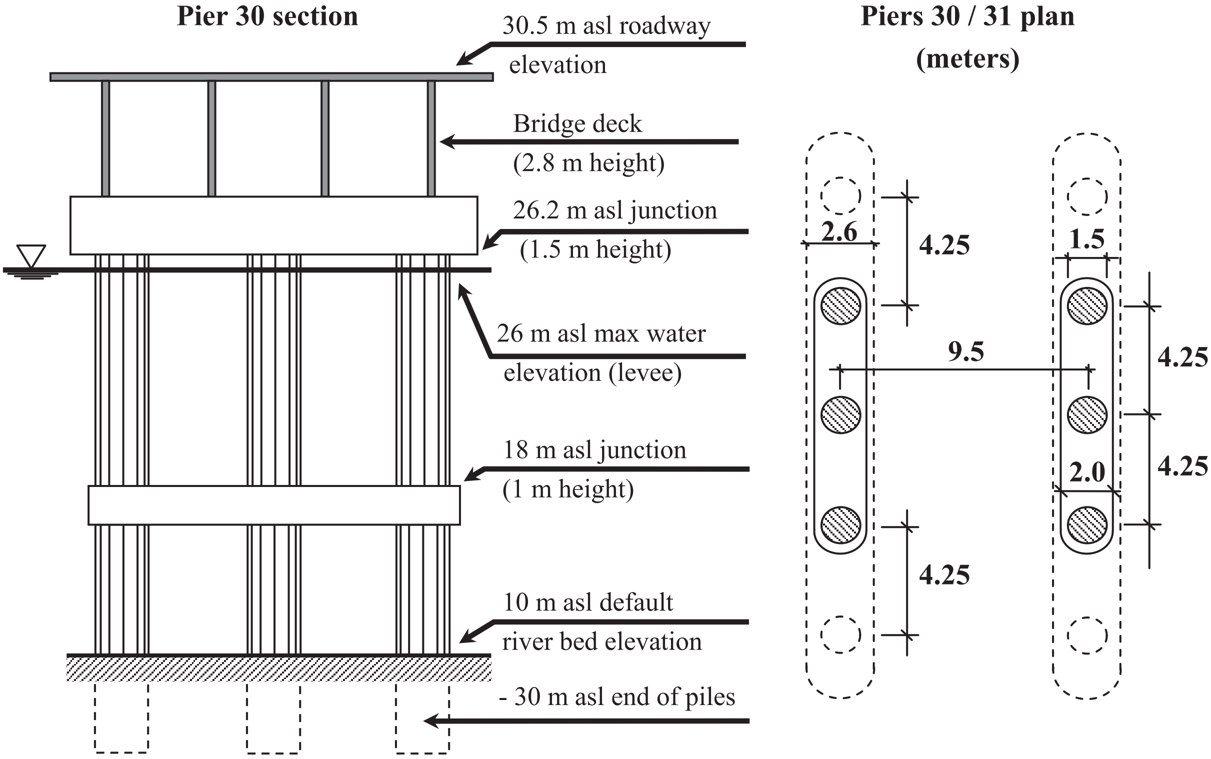


**Figure 2: Pier 30 section and plan. All elevations expressed in meters above sea level (m asl).**

Active loads are:

*Wind drag force*: $F_{wind} = f(V_{wind}, T)$

Here $V_{wind}$ is the component of the wind velocity perpendicular to the bridge (extreme values as large as 25 m/s); T is a binary variable (0/1) accounting for the presence of traffic on the bridge: in the case of no vehicles only the surface of the deck (168 $m^2$) is assumed for the computation; a scenario of presence of trucks for 50% of the bridge length increases the exposed area of 90 $m^2$ if the bridge is open to vehicles. For both cases, a value $C_D = 2$ for the drag coefficient is assumed. Resulting forces are shown in Figure 3a.

*Water drag force*: $F_{water} = f(h_{water}, D)$

Drag from water is computed only over the piers; the deck is assumed unsubmerged, as it is significantly higher than the adjacent levees (Fig. 2). Both water velocity (as large as 4.35 m/s for the highest water stages) and exposed area of the piers are calculated as unique functions of the depth of the water surface, $h_{water}$ (water depth with respect to the reference, unscoured river bed, Fig. 2). In particular, the presence of a scoured bed is not taken into account for the calculation of the drag force on the pier: it is assumed that the complex, three dimensional vortex structure within the scour hole exerts negligible drag with respect to that of the main flow over the base bed level; in other words, the value of the scour depth does not affect the calculation of the drag force from water. A value $C_D = 1.2$ is assumed for the drag coefficient for the first pile of the rows; for the others $C_D = 0.6$. Interactions within the two rows of piles are neglected.

Trapped debris in front of the group of piles forming the pier can significantly affect the water drag. The binary variable D (0/1) accounts for such effect: in the presence of debris piers are modelled as rectangular prismatic bodies having width equal to the distance between two rows of piles (11 m, see Fig. 2); the drag coefficient is assumed to be $C_D = 2$. Figure 3b plots drag forces resulting from the described model. The presence of debris is determined by real-time images from a camera (see Debris accumulation in Section IV).

*Loads from vehicles*: $F_V = f(T)$, $M_V = f(T)$, $F_{Vd} = f(T)$, $M_{Vd} = f(T)$

If the bridge is open to traffic (T = 1), a scenario must be considered where vehicles are present only on one roadway of the bridge, thus generating, other than a vehicles weight ($F_V$), a bending moment on the foundation ($M_V \approx 4200$ kNm). Furthermore, maximum force and bending moment due to deceleration a column of vehicles ($F_{Vd} = 206$ kN and $M_{Vd}$ respectively) are also taken into account.

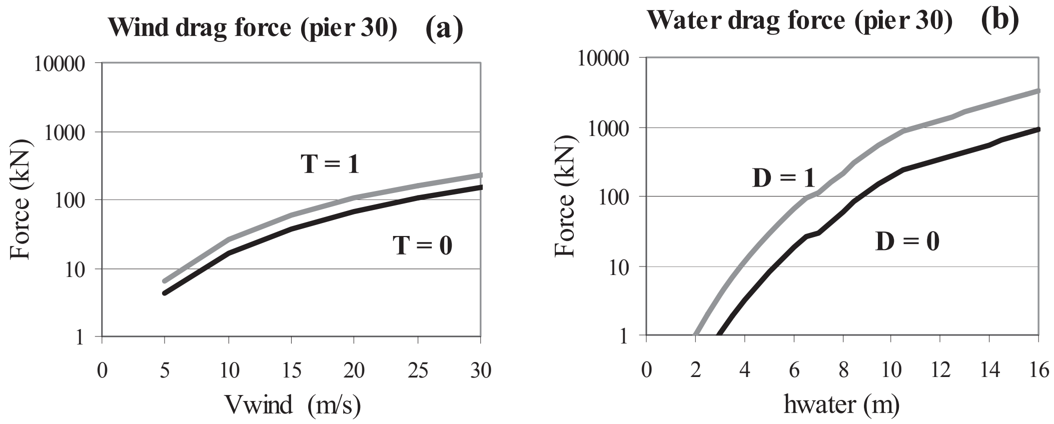


**Figure 3: Wind (a) and water (b) drag forces for pier 30.**

As explained above, the scour depth, $d_s$, does not affect the forces on the bridge. However, it affects the bending moments due to the forces with respect to the river bed level. The distance between the generic force and the river bed level, that is the arm of the force, increase with scour depth. The total bending moment is calculated as:

$$M = \sqrt{\left(M_{water} \pm M_{wind} \pm M_v\right)^2 + \left(M_{vd}\right)^2} \,. \tag{1}$$

In equation (1) the direction of the first three bending moments is parallel to the bridge axis, while the fourth one is perpendicular to it. As traffic is only considered as a binary variable, for the sign for $M_v$ the worst case (loads only on the downstream roadway of the bridge) is always assumed; on the contrary, the moment contribution from wind drag can be coherent or opposite to the other ones, depending on the direction of the wind. Finally, the functional relationship expressing the risk for the structure takes the form:

$$M/M_{\max} = f\left(V_{wind}, h_{water}, d_s, D, T\right), \tag{2}$$

where $M_{max}$ is the bending moment failure for the most critical pile (for the case under consideration, equal to 1850 kNm). A quantity of possible combinations of parameters can be discussed in order to evaluate the effects of the various terms in equation (2). In Figure 4 the risk factor $M/M_{max}$ is plotted for varying values of the water depth, $h_{water}$, and scour depth, $d_s$, constant high wind ($V_{wind}$ = 25 m/s), presence of debris (D = 1) and the two possible traffic conditions (T = 0, Fig. 4a; T = 1, Fig. 4b). The configuration in Figure 4b can be assumed as a worst case combination.

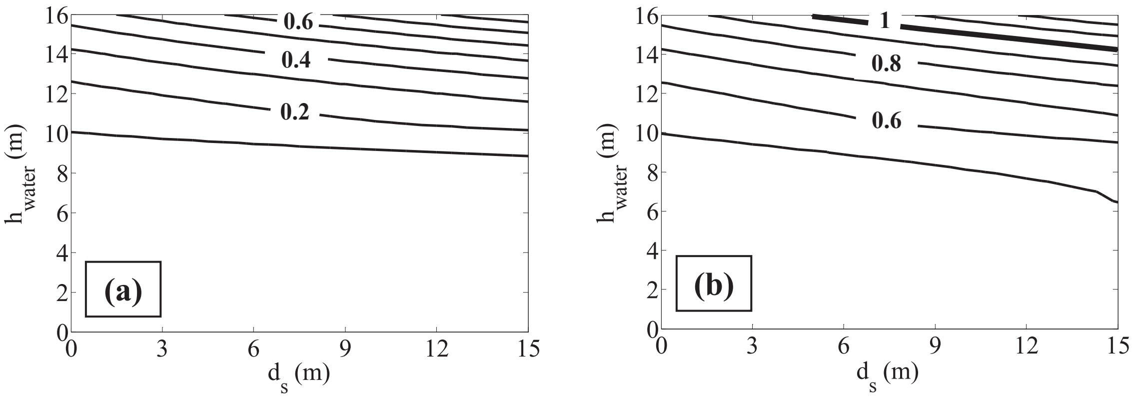


**Figure 4: Risk factor for (a) T = 0, (b) T = 1.**

Results in Figures 3 and 4 can be evaluated as follows.

i) Maximum values for wind drag and vehicles deceleration are relatively small with respect to those for water drag; it should be noted that the evaluation of water drag on clean piles is relatively realistic, while for the case of presence of debris, the adopted scheme, is highly conservative, as it assumes a uniform and non-porous debris packing along all the pier height.

ii) Relative effects of forces on the risk factor (2) are highly dependent on the scour depth. For unscoured conditions, the different terms have a comparable order of magnitude; for the highest scoured conditions, the momentum from water drag becomes the dominant term.

iii) For conditions where the bridge is closed to traffic (Fig. 4a) only extreme flood conditions and a heavily scoured bed could generate states close to critical. With no debris (D = 0, not plotted) the bending moment would be significantly reduced, so that pier 30 would be unconditionally stable.

iv) In the presence of traffic loads, conditions can become critical also without scour, if the wind is strong. Again absence of debris would lower the total bending moment to relatively safe conditions, even for scoured levels of the river bed.

As a consequence of previous considerations, the possibility of evaluating risk for the structure in real time not only allows for avoiding risks for users of the bridge, but also allows for preventing failure of the structure, as no critical conditions are expected in the absence of vehicles. On the other side, monitoring avoid unnecessary precautionary stops of traffic, as it would be in the absence of real-time data.

## IV THE MONITORING SYSTEM

The monitoring system involves a number of sensors, allowing for real-time estimation of the relevant variables for the calculation of the load on the bridge and, therefore, assessment of the risk level for the structure (Section III). Sensors are placed at different positions along the bridge (Fig. 5); signals are centrally collected in a control room located under the bridge, between two main beams. A real time device (PXI from National Instruments, a PC-based platform for test, measurement and control) serves to collect data from all the mentioned devices and manages storage, alarm generation and connections with the outside world. A wireless connection is used to send data to a remote station (Politecnico or Mantova Province headquarters).

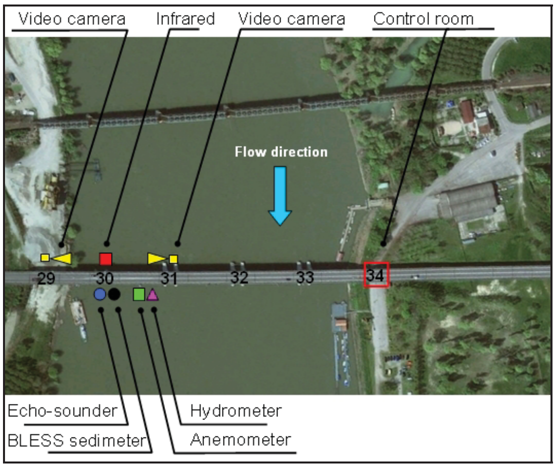


**Figure 5: Layout of the monitoring system.**

### *Wind velocity*

A weather station has been included to get an estimate of the wind actions on the bridge (Fig. 6a). The fundamental data are the wind intensity and direction. The averages, as well as the wind gust, are recorded on a 10 min base, as recommended by the specific standards to study the wind actions on structures [ESDU, 1993a]. Figure 6b shows examples of the output data.

### *Water depth*

A standard ultrasonic river stage sensor (Fig. 6a) is used to estimate water level and, therefore, water depth with respect to the reference river bed (Fig. 6c).

### *River bed elevation (scour)*

The measurement of the river bed elevation is the most relevant and difficult among the variables to be acquired for the assessment of bridge safety. For the monitoring station in Borgoforte, it was chosen to place two different and independent systems: an echo-sounder (Teledyne Benthos PSA-916) and an innovative optic sedimeter “BLESS” [Cigada et al., 2008]. The reason for the redundancy was the desire for a more robust evaluation of the position of the bed, especially in the difficult environmental conditions which are typical of a flood. Both sensors are mounted on the rear of pier 30: although this is not the expected location of maximum scour, it guarantees more protection with respect to impacts of floating debris; expected values on the front can be roughly estimated on the basis of typical shapes for the scour hole.

Positioning and orientation of the echo-sounder have proven to be critical issues, as the signal opens in a cone shape along its path in the water, allowing for multiple reflections, for instance from the bridge pier, therefore hiding the real bottom position. That is why a major problem has been designing the proper device to fix the sensor to the bridge pier, allowing position registration and removal for maintenance (it is an important task as the sensor is almost always immersed), with the additional possibility to remotely switch it off in case it gets dry, out of the water, as this can damage the sensor electronics, which needs to work at proper temperatures. As an example, Figure 7 gives a glimpse of the joint information provided by the water level measurements (top line) and the echo sounder (bottom line) during a light flood event, in which it is shown the contemporary increase of the river level and the digging at the pier base.

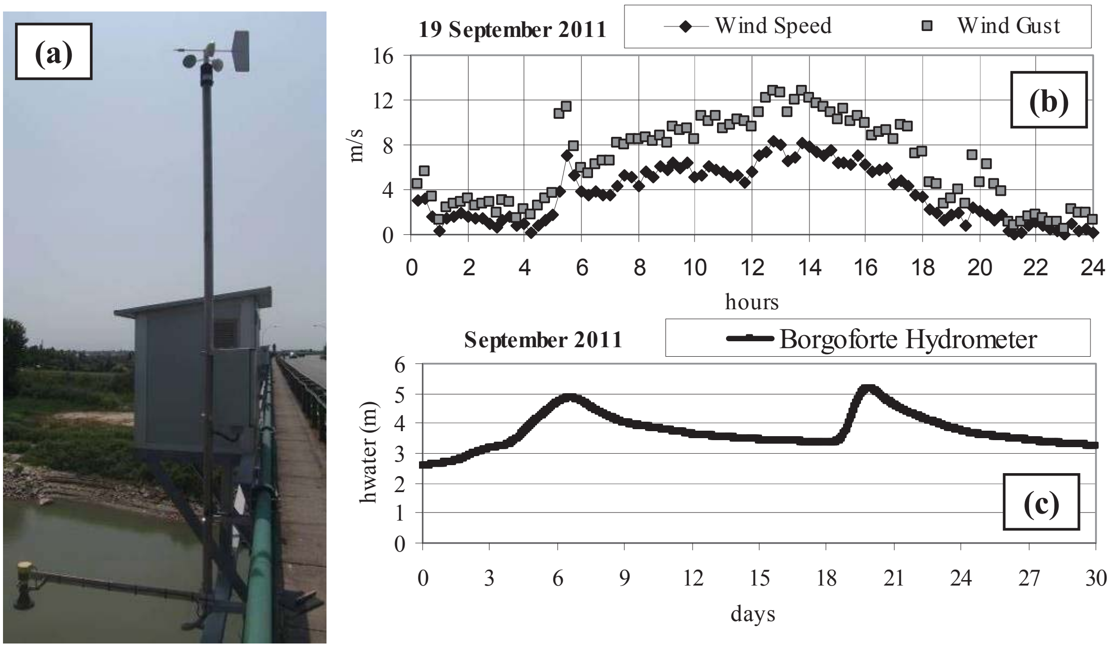


**Figure 6: (a) The anemometer (top of the figure) and the hydrometer (on the bottom); (b) an example of data from Borgoforte anemometer; (c) an example of data from Borgoforte hydrometer.**

The important step forward in this monitoring system has been the design and production of a new fiber optic based sensor, which has been patented as BLESS, Bed LEvel Seeking System [Cigada et al., 2008]. The working principle is the use of a series of Bragg gratings (FBGs) hosted on the same fiber, which is fixed along the bridge pier, to measure an array of temperatures [Hill, 1997]. The BLESS innovation is that the various FBGs are heated by an electrical circuit thanks to the Joule effect. The produced heat is then scattered around, due to conduction and convection, and the basic concept is that the temperature sensors in water should sense a lower temperature than those buried in the bed as the heat dispersion is much higher for the former ones. Since the date of installation of the monitoring system (June 2011) variation of the bed level were smaller than 0.7 m; since the resolution of the sedimeter (equal to the distance between two successive temperature sensors) is 0.5-1 m, no significant outputs from BLESS are available. Readers interested to more details about the technology can make reference to [Manzoni et al., 2011].

*Debris accumulation*

Two infra-red cameras regularly acquire images of the upstream side of pier 30 (Fig. 9a); on the basis of a subjective evaluation of the image (significant amount of trapped debris) the bridge manager chooses which value should be given to variable D (0,1).

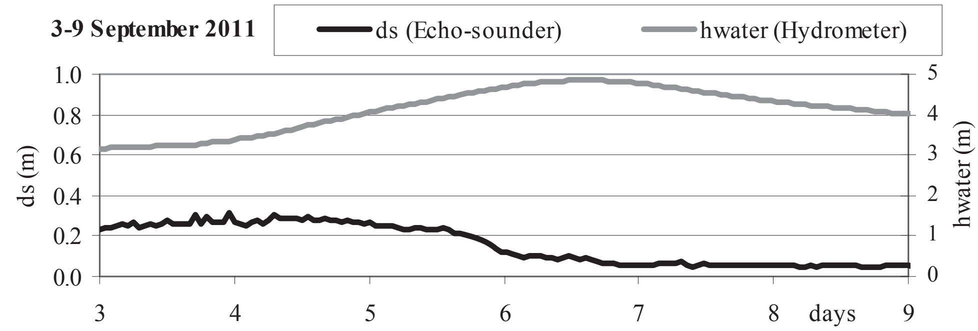


**Figure 7: The echo-sounder (black) and the hydrometer (grey) measures.**

## V RESULTS AND DISCUSSION

Figures 8 and 9 show the outcomes of the monitoring system and of the global dynamic risk evaluation during a (minor) event occurred in the period 4-18 November 2011.

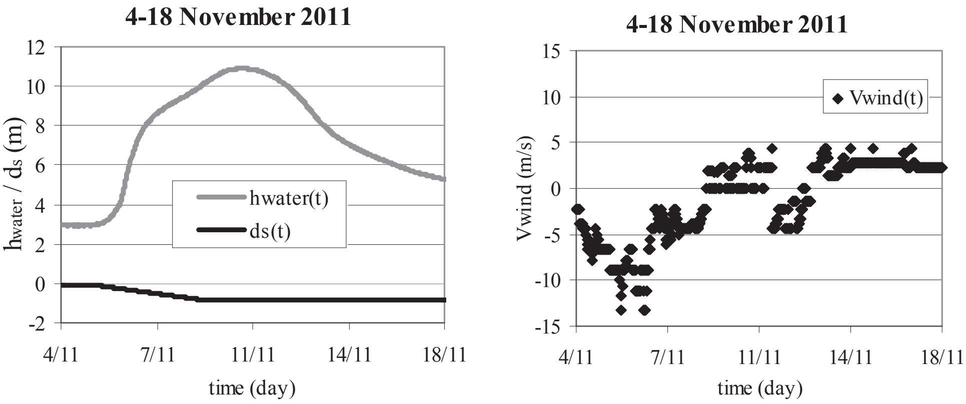


**Figure 8: Monitoring system data during flood in November 2011. Wind velocity is positive when it is in the same direction of the flowing water.**

The water level rose of about 8 m while the bottom of the river bed lowered of about 0.7 m. Wind was relatively intense on the 6$^{th}$ of November, but in the opposite direction with respect to the river (negative values in Fig. 8). In this case the wind bending moment was not stabilizing the structure because the water drag force was very small (depth was indeed only 3 meters, Fig. 8) and its bending moment was smaller than that due to the wind; for this reason the risk factor increased during 4-6 November (Fig. 9b) even if the water depth had not increased yet. After 6$^{th}$ of November the wind velocity was below 5 m/s, generating negligible drag on the structure (see Fig. 9b) and the development of the risk factor was linked to the flood event. No debris were present (Fig. 9a); however, also the curve corresponding to D=1 is plotted in Figure 9b, so that their potential incidence on the system can be appreciated.

Due to the mildness of the event, the risk factor varied only about 10% during the observation period, and was constantly well beyond any critical threshold. However, Figures 8 and 9 clearly demonstrate the capability of the whole system to provide different information and synthesise it into an overall index of the bridge risk with satisfactory accuracy and temporal resolution.

Reliability and robustness of the monitoring system should be assessed on a medium-term period, including some relevant hydraulic event. As long as no problems arise, the system appears as a non-structural alternative to consolidation interventions applied to the neighbouring piers: its main purpose is to allow evaluating the residual risk, in order to avoid casualties in extreme cases and, at the same time, reducing the incidence of unnecessary stops to the circulation. For the specific situation, however, as traffic plays a critical role within the forcing terms on the structure, proper choices about the possibility for vehicles to cross the bridge, significantly reduce the vulnerability of the structure.

After the reliability assessment, the final step of the project will be the definition of proper thresholds related to risk management scenarios, within a contingency plan. Two key issues should be mentioned within this respect:

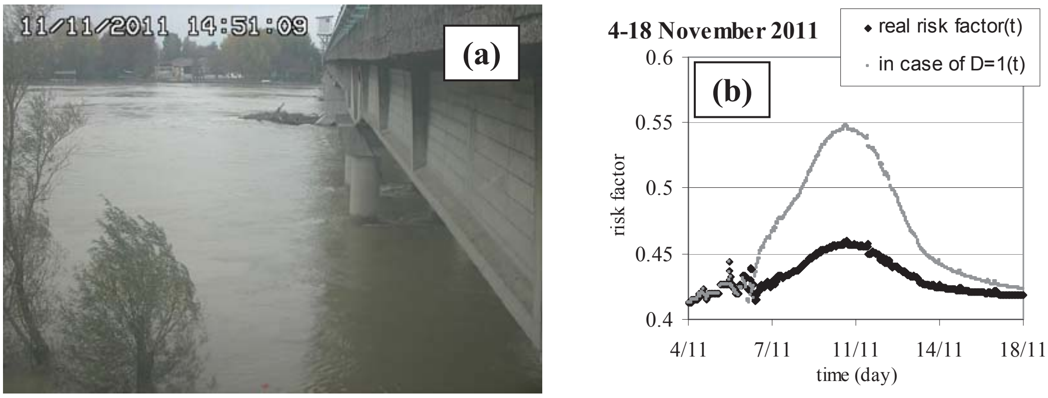


**Figure 9: (a) Image during the peak of the flood from upstream camera; (b) Risk factor during the event.**

1. For thresholds to be fixed, it will be necessary to define uncertainty bounds for the risk factor; uncertainties are mainly related to the models of external loads and of the structure (here not described). To avoid biased evaluations of the bridge vulnerability, no safety coefficients were introduced in models which, therefore, provide the best estimates of loads and resistance terms.
2. Management plans for the bridge should be completed within the more general event scenario of the territorial system. Given the general obvious rule of avoiding unnecessary closure of the bridge, acceptable risks should be defined on the basis of the strategic criticality of interruption of traffic during the event. For example, the bridge may be closed for regular traffic but not for emergency services (ambulances and fire trucks).

Technical evaluations (risk factor and related uncertainties) constitute are, therefore, only one part of the input for the final choices with respect to emergency procedures, which can be defined only within a global evaluation by the decision makers sharing the responsibility of the (flood) event.

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