Dynamic measurements for assessing bridge response to foundation scour

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Dynamic measurements for assessing bridge response to foundation scour

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ABSTRACT: Hydraulic actions are considered one of the main causes of bridge collapse worldwide. Among them, foundation scour plays an important relevant role. However, the assessment of foundation conditions is a difficult task, especially for existing bridges. Indeed, a complete characterization is often hindered by the limited accessibility and, in some cases, by the lack of available information on both the structural and the geotechnical design. On the other hand, an effective identification of foundation scour can be crucial for an accurate prediction of the long-term bridge performance, also for the planning of possible retrofit interventions. This paper presents the results of an experimental study carried out on a road bridge in Piedmont, severely affected by foundation scour and under strict surveillance by the Metropolitan City of Turin. Dynamic measurements were collected on the superstructure and the foundations. This enables to get an insight into the modal response of the deck and to detect asymmetries in the foundation behavior due to the presence of scour. This study demonstrates the potential of in situ measurements as a tool for the characterization of scour conditions of existing bridges and thus for the improvement of the resilience of transportation infrastructures.

1 INTRODUCTION: FOUNDATION SCOUR IN RIVER BRIDGES

The particular case study of interest, which will be detailed in the remainder of this paper, regards a riverside tract of a long road bridge. Indeed, even when bridges and viaducts just run alongside the river bank, without crossing it, they can be heavily affected by the time-varying conditions of the water-soil-foundation interactions.

In this regard, foundation scour is, by far, the most common cause of collapse for river bridges (Borlenghi et al., 2022) Recent examples of severely scoured bridges in Italy can be found in (Pizarro et al., 2020) and (Aimar et al., 2024).

Therefore, the scour phenomenon requires particular attention from geotechnical, structural, and hydraulic engineers, especially since its complex dynamics are not yet totally understood and easily predictable (Borlenghi et al., 2022; Ciancimino et al., 2021, 2022; Foti et al., 2023).

To this aim, this short contribution presents some preliminary results from dynamic identifications carried out on the deck and foundation caps of one segment of a very long road bridge, located in Inverso Pinasca (Piedmont, Northwestern Italy) and subject to heavy scour due to an ongoing change in the Chisone river course.

2 THE INVERSO PINASCA BRIDGE

The Inverso Pinasca bridge is part of a large set of renewal works performed between 2004 and 2005 to improve the road connection between Turin (the 2006 Winter Olympic Games host city) and Séstriere (a main ski resort) on the SP 166 road through the Chisone Valley. This route is inserted in an Alpine environment, with most of the traffic occurring during the winter season due to the influx of ski and mountain tourists. In

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particular, the small village of Inverso Pinasca (circa 600 inhabitants), as the Italian name *Inverso* (inverse) suggests, lies on the southern side of the valley, shadowed by the mountains. The majority of the other villages are situated on the northern (sunnier) side of the Chisone River. The bridge object of this study follows this southern bank before crossing the river after the village.

Figure 1. Side view of the Inverso Pinasca bridge in its full length, as captured during preliminary in situ surveys (February 3rd, 2023).

2.1 *Details of the tract of interest: Foundations and superstructure.*

The whole bridge (left side of Figure 2) measures 1849.90 m from end to end. The superstructure consists of four continuous decks, divided by expansion joints (that make all segments act as detached, independent units) and lying on 45 piers. the deck width is constantly 14.6 m, with one lane per direction.

The tract of interest is highlighted in red in Figure 2. It has a mixed profile, with rectilinear and curvilinear sections. These are located (as mentioned earlier) between the Chisone River on their East side and the small town of Inverso Pinasca on the West side.

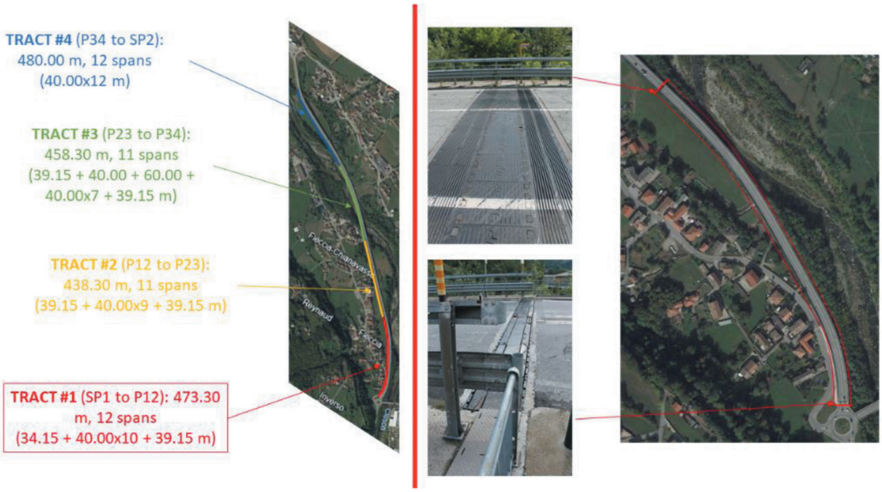

Figure 2. The four segments of the bridge continuous deck, with the one of interest (tract #1) highlighted in red and zoomed in on the right side. The two joints at its South and North ends are also portrayed.

The superstructure lies on deep foundations, with 8 piles per pile cap. These piles are particularly large (1.5 m in diameter), with a depth varying at each pier but included in a minimum of 14 m (pier P1, corresponding to the Southern abutments) and a maximum of 33 m (P24, out of the tract of interest here).

2.2 *Site-specific risks*

The area where the bridge lies is relatively seismically active, if compared to the rest of the Piedmont region. However, in absolute terms, it is classified as a low seismic hazard area, with an expected Peak Ground Acceleration (PGA) of 0.133 g (class 3S according to the local implementation of the Chapter 7 of the Italian NTC 2018 (Ministero delle Infrastrutture e dei Trasporti, 2018), considering a 10% probability of exceedance in 50 years). It is also worth noting the state-of-the-art seismic design of the bridge, where all bearings rest on seismic isolators.

From a hydrogeologic perspective, the area is free from landslide hazards, with only some slow ground movements on the north bank (hence, on the opposite side of the Chisone River) and no avalanche hazard due to the relatively warm climate year-round at the valley bottom.

Instead, the whole length of the infrastructure is classified by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA)[1] as a high flood hazard area. The last major flood (October 2000, when the bridge of interest was yet to be constructed) caused the collapse of a nearby river crossing. Therefore, from a multi-risk assessment point of view, the potential scouring of the bridge piers can be identified as the main potential source of danger.

2.3 *Current scouring state*

The repeated alluvial events that affected the Chisone valley since the construction year (for instance, in 2010 and 2016) induced a migration of the main channel of the river, which has gradually shifted towards the orographic right, in correspondence with the bridge piers. The migration has resulted in strong undermining of the pier foundations in correspondence with a portion of the bridge, namely the one between P8 and P11. The modified shape of the streambed resulted in the exposure of the top part of foundation piles and general scour of piers, with depths up to 3.8 m for pier P9 (computed from the bottom surface of the pier cap) and 3.5 m for pier P10. It has to be remarked that the scour hole is not symmetrical because of the presence of a scarp more or less around the longitudinal axis of the bridge. Therefore, only half of the foundation is exposed. Furthermore, the scour hole below pier P8 has been partially refilled with coarse soil to prevent further erosion in this portion.

A map of the surveyed piers is reported in Figure 3, with the respective photo documentation of the scouring state as of mid-2023.

3 THE DYNAMIC IDENTIFICATION CAMPAIGN

The aim of the dynamic identification campaign was two-fold. On the one hand, it focused on the estimation of the modal parameters of the superstructure. Furthermore, it targeted peculiarities in the soil-structure system response to have an indirect insight into the influence of scour on the dynamic response, in terms of asymmetric features in the behavior. For this purpose, the survey focused on a portion of the bridge including parts affected and not affected by scouring. Indeed, the relative response can directly provide indications about the scour influence.

The setup included 13 PCB 3701G3FA3G uniaxial capacitive sensors, mainly located along the external longitudinal beams of the deck (Figure 4). The asymmetric location was mainly dictated by the accessibility of the beams on the river side, due to the presence of the scarp. In

1. https://idrogeo.isprambiente.it/app/pir

addition, 5 PCB 356B18 triaxial capacitive sensors were located on the longitudinal beams, in correspondence with the piers, to track the complete motion and to capture the influence of the seismic bearings.

Furthermore, high-sensitivity (10 V/g) PCB 393B04 piezoelectric sensors were located on the top of the foundation pad, both in uniaxial vertical or multiaxial configuration, to track the motion of the pier. The considered piers were P7, P8 and P9, each characterized by a different scour magnitude (Figure 5). For all the piers, a minimum sensor layout was adopted, consisting of four vertical sensors on the corners plus one/two horizontals, to track the relative asymmetries in both the vertical response and the horizontal response. However, being P9 the most deteriorated pier, a dense layout was adopted for this.

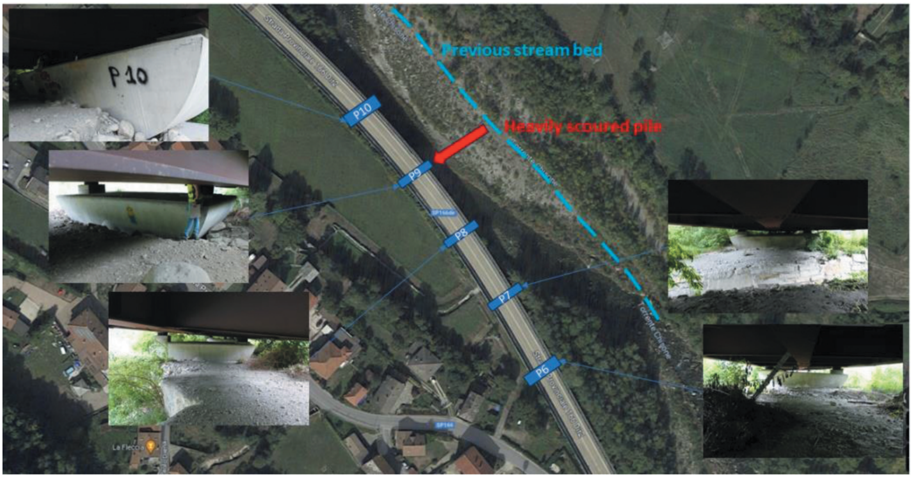

Figure 3. The current (mid-2023) scouring state at the pier foundations of interest. The most critical one (P9) is indicated by the red arrow. The blue dashed line represents the river course as of 2004 (during construction).

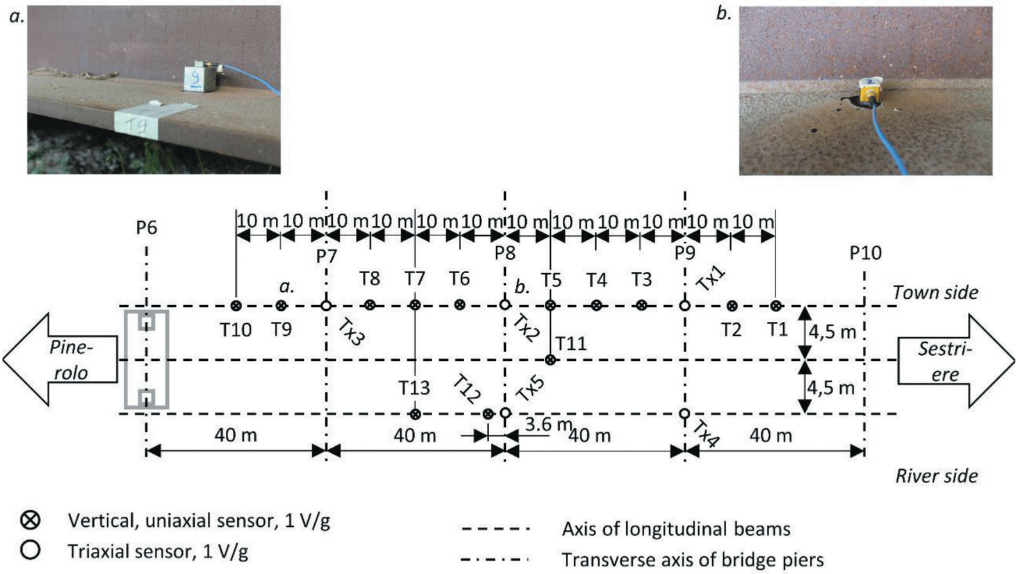

Figure 4. The sensor layout for the bridge deck, including a picture of the capacitive uniaxial (a) and piezoelectric triaxial (b) Accelerometers.

The acquisition was carried out through a 40-channel, LMS Siemens SCADAS acquisition device, using a 256-Hz sampling rate.

The limited number of channels and of high-sensitivity sensors compared to the inspected locations forced to perform the measurements through multiple setups. In all the setups, the

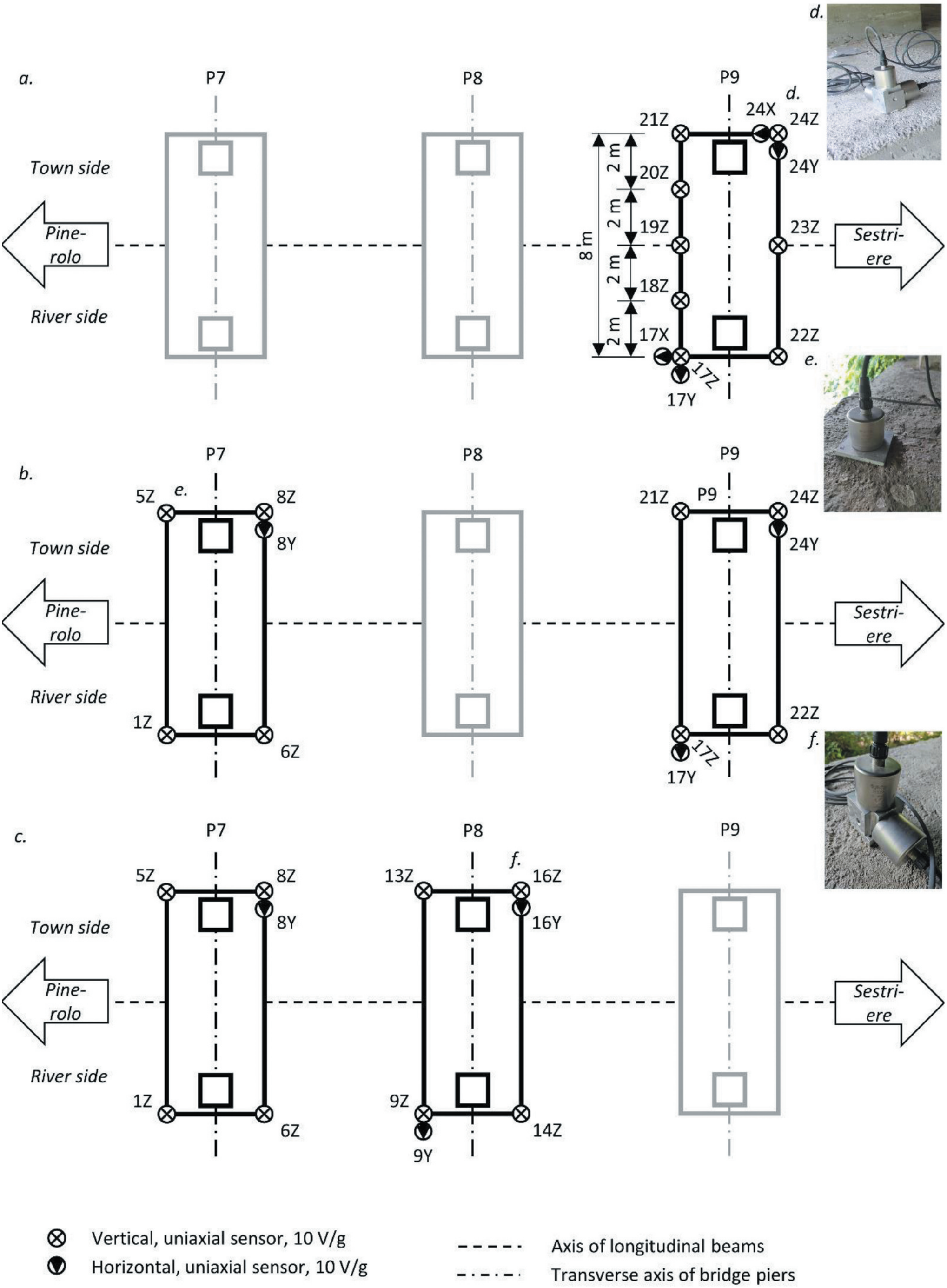

Figure 5. The first (a), second (b) and third (c) sensor layouts for the pier caps, including a picture of the high-sensitivity accelerometers in uniaxial (e), biaxial (f), and triaxial (d) configuration.

sensors on the deck and part of those installed on pier P9 were kept unchanged, also to provide a reference for the normalization and harmonization of measurements, whereas the high-sensitivity sensors were located to measure each couple of piers (i.e., P7-P9, P7-P8 and P9 only; see Figure 5). The rationale behind this strategy is to address the relative response of each couple of piers, with different scour conditions, to have an insight into the effect of scour.

4 PRELIMINARY RESULTS

The results described in this section refer to the first insights gained from a preliminary analysis of the gathered acquisitions, in terms of the response of the bridge deck and pier foundations.

4.1 *Insights from the bridge deck*

From a preliminary analysis of some of the signals acquired from the sensors deployed on the bridge deck, the main vibrational modes of the bridge deck in the tract under investigation seem to be a first vertical flexural mode at circa 2.20 Hz and a torsional one at 2.44 Hz. These values are averaged over six different ambient vibration acquisitions, analysed with the Automated Operational Modal Analysis code described in (Civera et al., 2022; Mugnaini et al., 2022). Both modes appear to have a relatively high damping, with the damping ratio ξ being larger than 2.5% in both cases. This is most likely due to the presence of seismic isolators at all bearings.

Furthermore, the detailed analysis of all modes highlights an asymmetry between the town- and the river-side. That is to say, the peak relative displacement (corresponding e.g. to the antinode at midspan for mode #1; see Figure 6.a) was found to be higher on the side of Inverso Pinasca, in all acquisitions. Considering six signals and the first mode shape, this difference in peak amplitude can be estimated at 28.51±2.08 % ($\mu \pm \sigma$), thus, almost a third. Considering that all the sensors start from their zero, the slight transverse inclination of the deck should not have a direct influence. However, some numerical simulations of the uncalibrated FE model of the deck only (Figure 6.c) show that the leftward curvature of the deck naturally induces some higher vibration amplitudes on the riverside, as was also well expected. Nevertheless, these asymmetries could be (at least partially) also exacerbated by the absence of the scoured ground on the riverside (due to the loss of stiffness). Therefore, these aspects will need further studies to be properly investigated and understood.

4.2 *Insights from the pier caps*

For a quick assessment of the foundation response, this study estimated the RMS vertical acceleration (here, labelled as a_z) recorded at the vertices of each pier cap, consistently with the approach adopted in (Foti & Sabia, 2010). For a more reliable estimate, a_z was computed from 10-s long time windows extracted from the recorded data, each corresponding to the passage of a vehicle on the bridge deck. Figure 7 shows the estimated a_z for piers P7 and P9, that is, the ones with the least and the most scoured foundations. Results are clustered according to the side of the load application. Furthermore, they highlight the trend on the upstream side and the downstream side, to investigate asymmetries both in the town-river direction and along the longitudinal axis of the bridge. Finally, for each pulse considered, a_z data are normalized with respect to their average value, to remove the influence of the load entity on their magnitude.

In all the cases, a larger a_z is observed at the side corresponding to the load application, as expected. However, some relevant differences can be observed when comparing the dynamic behavior of P9 and P7. On the one hand, the spatial distribution of a_z is similar when vehicles pass on the town side, in terms of asymmetry. Instead, for loads on the riverside, a_z is quasi-uniform in P7 (as the normalized value is almost close to the unit) whereas larger variations are observed for P9. This means that, for the same loads, the vibration levels in P9 are highly asymmetric compared to P7, due to the stiffness variations induced by foundation scour. On the other hand, in P9, a_z is significantly larger downstream than upstream. Notably, this is observed both on the town side and on the river side, for all the considered load pulses and application locations. Instead, this discrepancy is smaller in P8 (not reported here) and almost negligible in P7. This result was somewhat unexpected, as the erosion mostly acts along the longitudinal axis of the bridge and should not produce relevant differences in the response between upstream and downstream. Instead, this evidence may indicate that stiffness variations in the soil-structure system due to scour also occur along the flow direction of the river – and not only in the transverse direction, as it may be expected from the available information. This may be a consequence of the curvature of the main river channel, which results in a complex morphology of the scour hole.

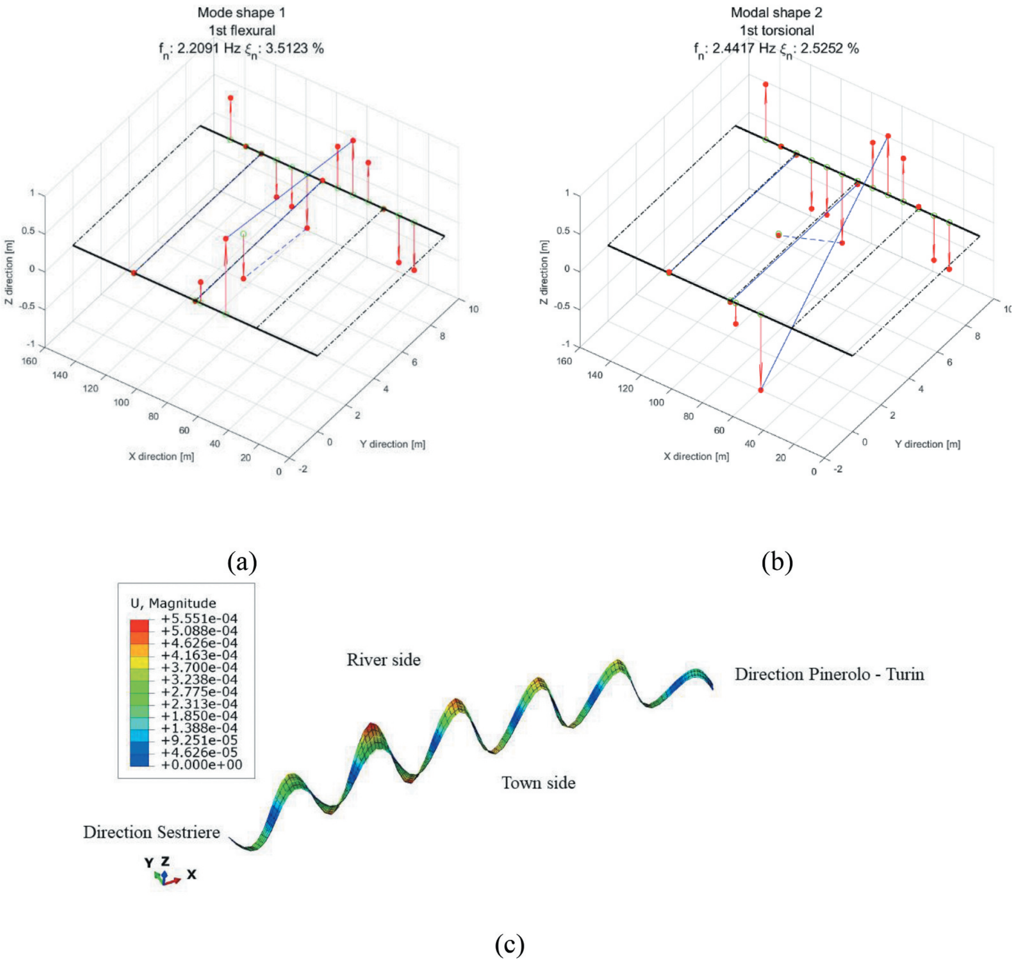

Figure 6. (a-b) The mode shapes identified from the deck bridge dynamic response (example taken from the ninth acquisition). The blue lines connect the modal displacements captured by the accelerometers located on the town side of the deck with their counterparts on the other side (or at mid-width for T5-T11). The black lines represent the deck layout in its undeformed shape. (c) First flexural mode, according to a preliminary simulation (uncalibrated, deck only) run on Abaqus 2019.

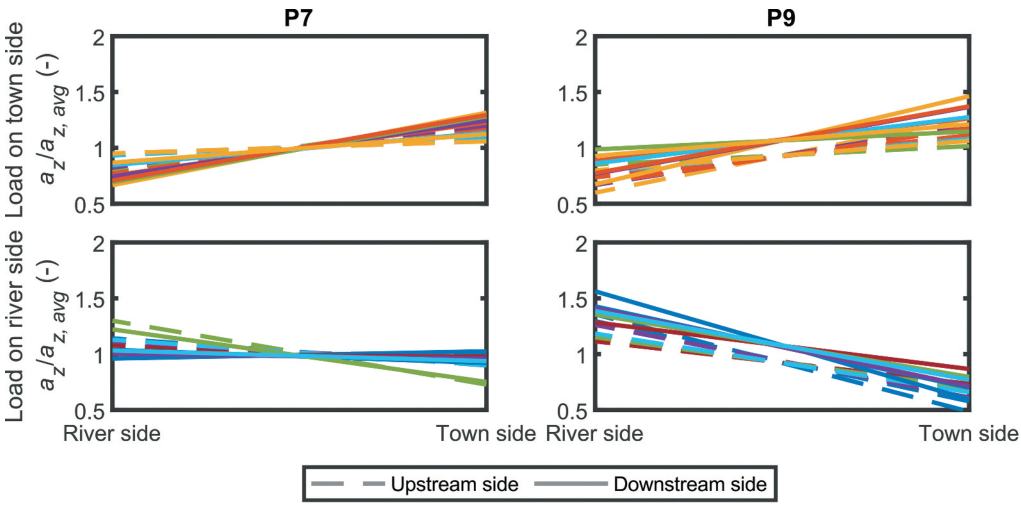

Figure 7. Estimated normalized acceleration RMS at the pier caps, for P7 and P9 and for loads applied on the town side or the river side. Results are clustered according to the considered side of the pier cap (i.e., downstream and upstream). Each color corresponds to a specific load (i.e., vehicle moving on the deck), with the continuous line representing the vibration level observed downstream and the dashed line representing the response on the upstream side.

5 CONCLUSIONS AND FUTURE WORKS

This study described the experimental campaign carried out to investigate the dynamic response of a multi-span bridge near to Turin, which is affected by foundation scour. The survey addressed both the deck and the foundation response over a portion of the bridge, which includes scoured and unscoured piers. The rationale behind this strategy is to address the relative response of nearby portions of the bridge, with different scour conditions, to have an insight into the effect of scour. Preliminary results from the processing of experimental data demonstrated the presence of asymmetric behavior on both the deck modal shapes and the piers vibration magnitude, which can be attributed to the inhomogeneity of the distribution of soil stiffness due to scour. Ongoing studies, to be reported in the near future, are focusing on more detailed assessment of scour effects on the bridge pier caps and deck. As the local administrative entity (Città Metropolitana di Torino) is currently planning for hydraulic and geotechnical countermeasures, future works will report as well the dynamic behaviour of the target infrastructure before and after interventions.

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