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Scour monitoring on bridge pier: two French returns on experience

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ABSTRACT

Scour represents a significant contributing factor in structures destruction. Managing the scour risk on bridge piers and abutments, road or rail type, exposed to natural hazards constitutes a major challenge to sustainable development and land use planning. One of major issues for managing this risk is the monitoring of structures. In this context, the work presented here provides a French return on experience. Two real sites were indeed selected and instrumented. The instrumentation was carried out in an exhaustive manner: velocity fields, bathymetry, water levels, and even vibration measurements on the last one, etc. Following the acquisition of numerous continuous measurements, details on data processing and a first feedback are provided.

INTRODUCTION AND BACKGROUND

In order to better control the risks associated with scouring, many monitoring systems have been developed, based on intrusive or non-intrusive devices and direct or indirect, point or continuous, fixed or mobile measurements, using a variety of technologies (electrical, electromagnetic, acoustic, magnetic, fibre optic, etc.) (Boujia et al. 2019, Brandimarte et al. 2012, Prendergast and Gavin 2014, Wang et al. 2017). Most of these monitoring systems focus only on the bathymetric (pit depth) aspect of the scour problem but do not correlate it with flow conditions.

However, erosion and scouring phenomena strongly couple hydraulic dynamics (height, velocities, etc.), the sedimentary surface (mass) and the structure in the flow through non-linear processes: erosion threshold, transport, deposition, etc. Being interested only in the depth of the pit (the sedimentary level) or in the water level does not allow to account for all the phenomena on site. There is therefore a real lack of field experience in the continuous monitoring of flow and bathymetry.

In order to better understand the scouring phenomena, continuous monitoring on structures was therefore envisaged, carried out and used within the framework of the ANR SSHEAR project (Chevalier et al. 2021). In detail, based on a study of the databases of the management partners, 7 study sites were selected with the objective of being representative (Salavati et al. 2017). Conventional survey tests and complementary techniques were carried out to better characterise the scoured site. This work led to the detailed monitoring of three pilot sites: the A71 motorway viaducts over the Loire river at Orléans (piers in the bed of a river), the St Loup bank on the Allier river and the masonry arch rail bridges at Isle over Aurence river.

Two of these sites (bridges over Loire and Aurence) were also selected for the installation of permanent instrumentation. A specification for the instrumentation was then established (Florens et al. 2018) leading to the development of 2 specific instrumentation solutions (Larrarte et al. 2020) allowing the continuous monitoring of key parameters for the understanding of scouring phenomena: bathymetry (sediment level) and velocity profiles (2D or 3D).

We will first review the principle of the instrumentation and its implementation. We will detail the various data acquired and their relevance to existing data. We will then propose a statistical treatment of these data to characterise the different aspects of the potential scouring processes at the level of the structures: water height, velocities, sediment levels, soil-structure interaction, etc. Finally, we will draw conclusions from these initial analyses with a view to establishing a return on experience from these two instrumentations.

SITE DESCRIPTION AND MONITORING SYSTEMS

Aurence bridge. The first site to be instrumented was the SNCF rail bridge over the Aurence river at Isle near Limoges (Haute Vienne department, France). It is a masonry arch structure characteristic of the secondary rail network located on the Limoges-Angoulême line (Fig. 1). This site is affected by scouring near the left abutment. The masonry abutment is partially collapsed and numerous blocks in the river bed have been found. At the foot of the abutment, a scour hole of 1.7m in length and 0.5m in depth was measured. A bathymetric survey by Cerema/LR Blois confirmed that an eroded area exists under the bridge with an even deeper section on the upper side of the river. It was decided to locate the sensors in this area.

The complete installed set-up is shown in Figure 1. It is composed of:

- an Ijinus LNU06V3-82-3G water level meter to measure the water level,
- a Ubertone UBF156 Ub-flow ultrasonic profilometer mounted on a vertically movable board to measure velocity profile and water depth,

- a HIK Vision 4 MP WDR camera to monitor the test device,
- an acquisition and transmission box powered by 2 solar panels.

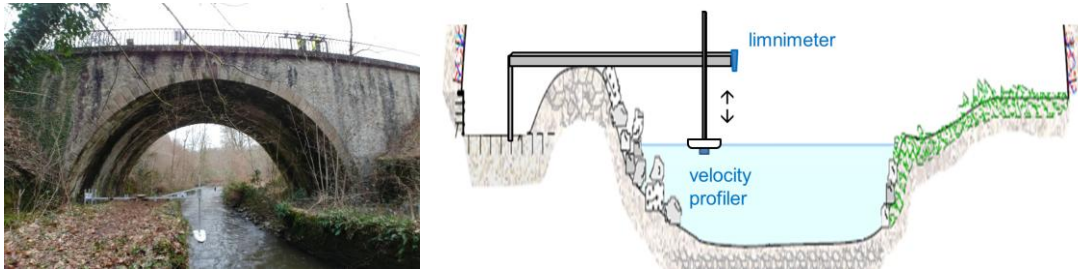


Figure 1. Site of the bridge over the Aurence River near Limoges (France): (left) view of the instrumented site and (right) scheme of the instrumentation (Chevalier et al. 2021).

The acquisitions take place every 5 minutes. Technical details are given by Larrarte et al. (2020). The Ub-flow profilometer is equipped with 2 transducers allowing the reconstruction of a 2D velocity profile. It should also be stressed that the technical constraints of such devices (depth of investigation, Nyquist limit on velocity measurements by Doppler effect, "dead" zone, etc.) imply a certain number of choices and numerical treatments (Larrarte et al. 2020, Chevalier and Larrarte 2022) which will not be detailed here.

A71 viaduct. The A71 motorway viaduct (Cofiroute) over the Loire at Orléans (Loiret department, France) was the second site instrumented. As shown in Figure 2, the bridge is approximately 400 m long and rests on 6 supports, 4 piers located in the river bed (noted P2 to P5 from the right bank to the left bank) and two abutments (C1 and C6).

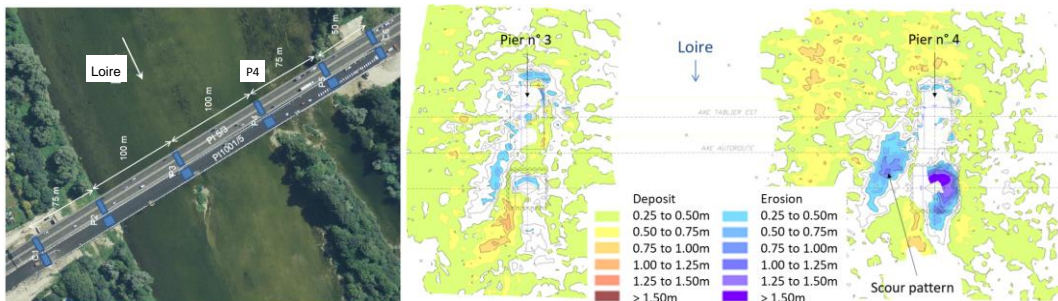


Figure 2. A71 motorway double viaduct in Orléans (France) over Loire river: (left) aerial view of the bridge and (right) bathymetric surveys comparison between January 2018 and May 2016 (Chevalier et al. 2021).

Cerema/LR in Blois has a long-standing partnership with the motorway company Vinci Autoroutes/Cofiroute, which manages the structure, and has been assessing scour on various bridges for many years. SONAR bathymetry was carried out in 1993, 2004, 2011, 2016 and 2018 showing active erosion/deposition sites, particularly on the left of the support of pier P4 as shown in Figure 2. It is this area that was therefore decided to monitor.

The instrumentation at this site, which is more complex than that at Aurence, includes:

- a Valeport VRS-20 water level meter on the bridge to measure the water level;
- a Kongsberg Dual Axis SONAR to scan the bathymetry;
- an ADCP Teledyne RDI Monitor 1200kHz speed profiler to measure the 3D speed field.

The SONAR and ADCP were mounted on a raft. The sensors are connected to a computer and the measurements are transmitted to a data server.

Finally, three accelerometers, one tri-axial PCB 629A11 under the bridge deck and two mono-axial PCB 393B31 (though vertical axis and hydraulic flow axis) on the top of the bridge pier complete the set-up.

DATA AND ANALYSIS - AURENCE BRIDGE

Water and sediment levels. Figure 3 shows the water level results (defined to a constant, chosen so that, at the start of monitoring, the water level is equal to the water height measured by the Ub-flow profilometer) obtained over 3 months with the Ijinus water level meter. They are in very good agreement with the data of the hydrometric measurement station of the “Hydro bank” system (<https://hydro.eaufrance.fr/>) located approximately 2km upstream. We can also observe a very good agreement between the rainfall at the site and the water levels observed: the Aurence river is a small and very reactive river.

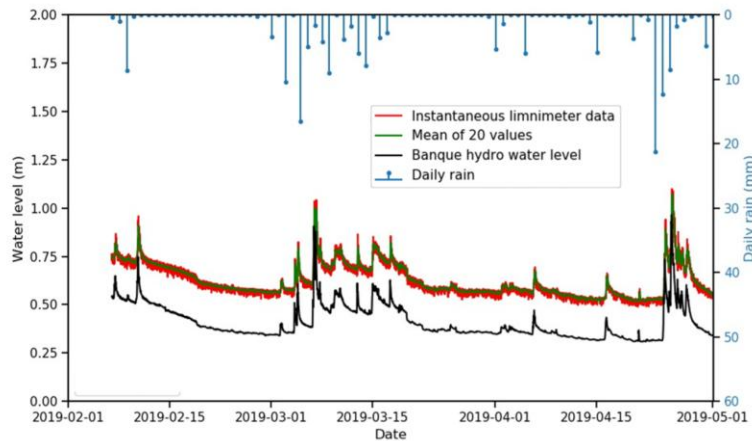


Figure 3. Monitoring of water levels and rainfall over 3 months at Aurence Bridge.

The Ub-flow measurements were used to measure both the water height and the velocity profile. Figure 4 shows the profile of the backscattered signal intensity as a function of time at a certain distance from the surface (black curve), over the month of March 2019. High values indicate the presence of an obstacle (a strongly backscattering surface in practice), the first intensity peak is characteristic of the presence of the bottom. The high backscatter values remain at the same level (notably $z=0\text{m}$, corresponding to the sediment bottom). No significant difference (greater than the order of a centimeter) and therefore no erosion was observed over these 30 days as well as over the 9 months of the complete study.

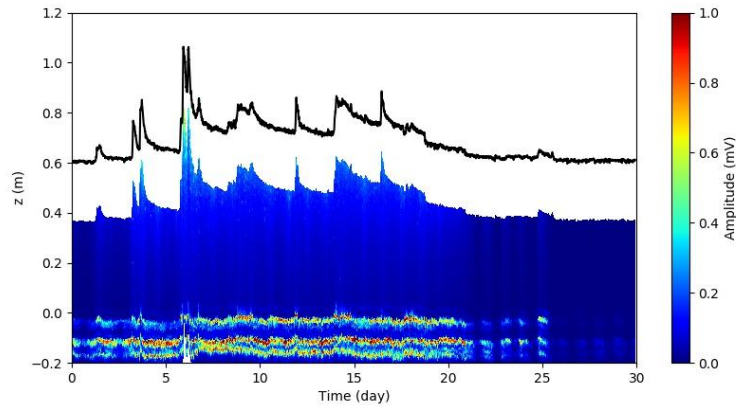


Figure 4. Evolution of the amplitude profile of the Ub-flow backscatter signal in March 2019. The black curve represents the position of the free surface.

Characterisation of the velocity field. Several velocity data are recorded by the Ub-flow according to different configurations (maximum velocity, depth of investigation, average...). Figure 5 shows, as a function of time, the velocity profile (horizontal component in the plane of the Ub-flow) obtained from various configurations of the Ub-flow. This profile is derived from a numerical pre-processing in Python allowing the rectification of signals subjected to Nyquist limits (Fischer 2004, Larrarte et al. 2020).

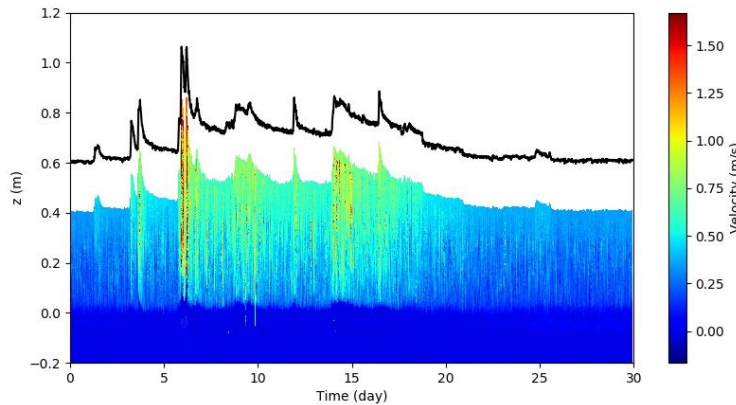


Figure 5. Evolution of the horizontal velocity profile from the Ub-flow in March 2019. The black curve represents the position of the free surface.

Characteristic velocities (close to the surface) can then be deduced. Figure 6 shows the evolution of these velocities for different values of water height. The evolution of the average height is also represented (colour scale). This makes it possible to obtain a characteristic curve of the water course. It should be noted that no notable hysteresis is observed

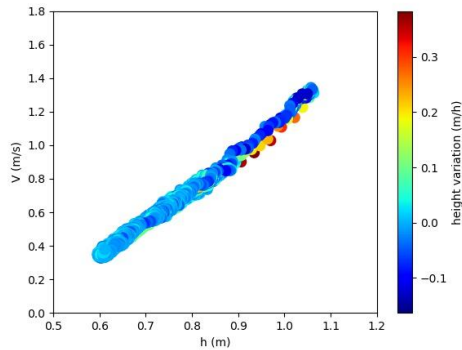


Figure 6. Flow characterization in March 2019: velocity as a function of water level.

Statistical analysis. To analyse more finely the phenomena, it is however appropriate to exploit the instantaneous velocity data to the maximum. For that, the velocity profiles were analysed by set of 5 successive instantaneous profiles and adjusted by a Cheng law (Cheng 2007):

$$U(z) = U_{max} \left(\frac{z}{h} \right)^{1/m} \quad (1)$$

where $U(z)$ is the average velocity in the direction of the current at a distance z from the bottom, U_{max} the maximum velocity of the law in the vicinity of the surface, h the height of water and $1/m$ the exponent of the power law with $m=3.5$. It is possible to use other fits, such as Coles' law (Cole 1956), with comparable results and analysis (Larrarte et al. 2020, Chevalier and Larrarte 2022).

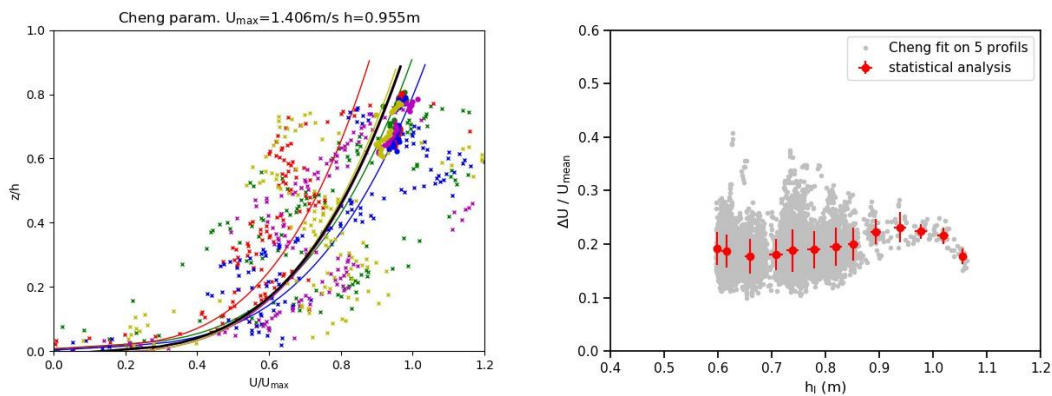


Figure 7. (left) Examples of 5 successive profiles (5 minutes apart) of scaled velocities fitting by a Cheng's law on each profile (coloured curves) or on the whole data (black curve). (right) Evolution of the characteristic deviation from velocity data to the adjustment (Cheng's law on 5 successive profiles) as a function of the water level for the month of March 2019 (all values, mean and standard deviation).

An example of such adjustments is shown in Figure 7. Large fluctuations in measurements are observed both when considering a single profile and between the 5 successive profiles. This is a characteristic of the flow in a real river which is not as controlled as in a

laboratory channel. However, a good fit can be obtained with the equation (1) to evaluate shear rates for example. These measurements allow characterizing the different hydraulic conditions of the river. A statistical analysis can be done on the dispersion of the instantaneous measurements compared to the adjustment. This analysis is represented on Figure 7. It can be identified that the deviation of the speed represents approximately 25% of the average speed, whatever the water level making it possible to characterize the deviation of the instantaneous values of speeds with the averaged profile in real situations.

DATA AND ANALYSIS – A71 VIADUCT

Water and sediment levels. Figure 8 shows the water level results obtained over 4 months with the Valeport VRS water level meter. They are in very good agreement with the data of the hydrometric measurement station of the “Hydro bank” system (<https://hydro.eaufrance.fr/>) located upstream. We can also observe a quite good agreement between the rainfall near the site.

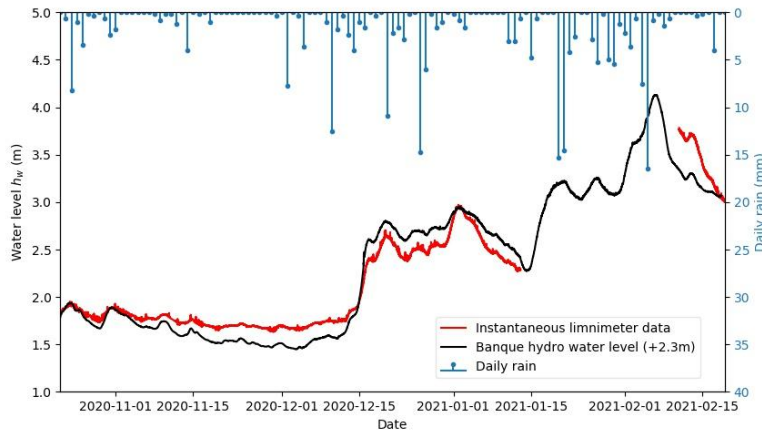


Figure 8. Monitoring of water levels and rainfall over 4 months.

The SONAR takes bathymetric measurements every hour. In contrast to the Aurence monitoring, a significant part of the sediment surface (and not a single point) can be monitored as shown in Figure 9. Beyond the average flow depths that can be evaluated and correlated with the water level measurements, it is therefore possible, with this configuration, to follow the dynamics of the whole scouring pit. However, this requires the implementation of correlation algorithms between the various bathymetric surveys in order to be able, on the one hand, to spatially reposition the data and, on the other hand, to identify the evolutionary zones. A first simple analysis shows that the average water depth evaluated with the SONAR evolves in a coherent way with the water level measured with the Valeport VRS gauge (Fig. 9).

Velocity field. Figure 10 presents, over a period of one month, a follow-up of the speeds with the ADCP speed profiler. The upper velocities measured at a distance of between 0.60 and 1.20m from the surface (average of the ADCP measurements) are compared with the water level monitoring. The dynamics of the two data are extremely similar with a decrease during the first

15 days and fluctuations thereafter with an almost stable water level. A more advanced treatment of the data (with taking into account their fluctuation) could thus probably lead to the obtaining of a "taring curve" of the flow as considered in Figure 6 for the case of the instrumentation on the Aurence Bridge.

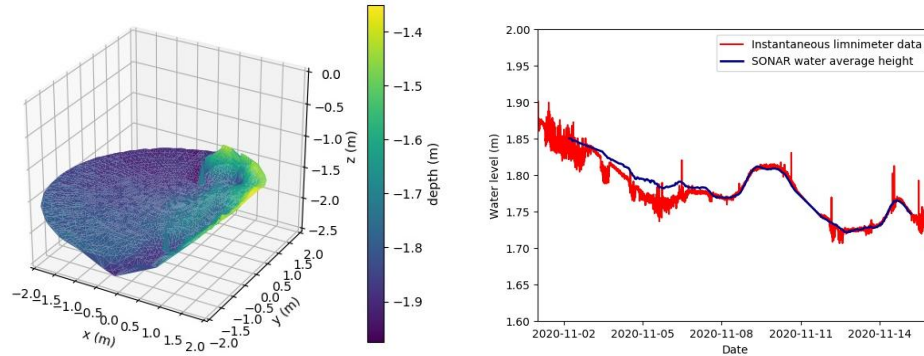


Figure 9. Monitoring of sediment surface by SONAR and comparison between SONAR average water height and Valeport VRS water level over 18 days.

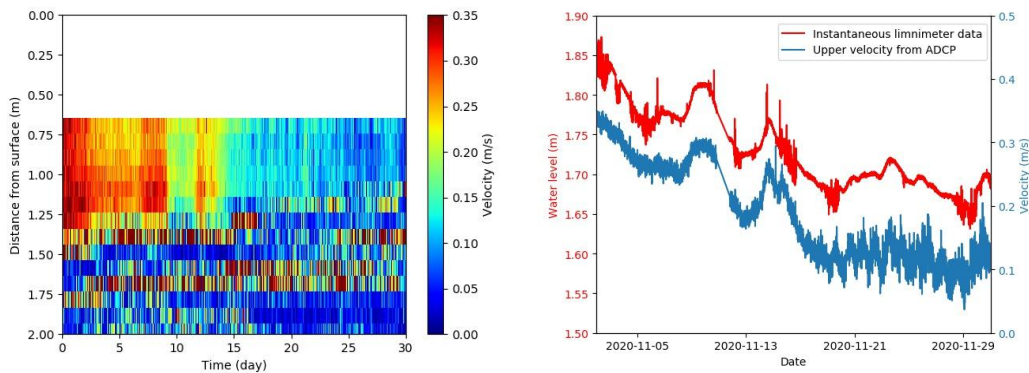


Figure 10. Monitoring of velocity profile and water level and max velocity over 1 month.

Vibration analysis. Scour assessment using vibration-based monitoring is performed by analyzing the changes in natural frequencies over time. This method has been shown to be feasible through laboratory tests (Bao et al. 2017, Boujia et al. 2020) and offers significant advantages compared to other methods (Wang et al. 2017). In fact, from the response of the bridge piers, the health of the structure can be monitored in real time with global information including a change in boundary conditions such as scour. An inverse method is used to identify the mechanical parameters of the pier through natural frequencies (Shinoda et al, 2008). However, natural frequencies are highly sensitive to environmental factors such as temperature and external excitations (traffic loading and wind essentially). In that way first step is to filtering signals to reduce noise by using correlations between signals (Belmokhtar et al 2022). Then, a correction must be made for temperature effects. Figure 11 plots the daily natural frequencies of bridge pier P4 (Figure 2) over time and includes an example of temperature correction using linear regression. The evolution of natural frequencies can then be studied.

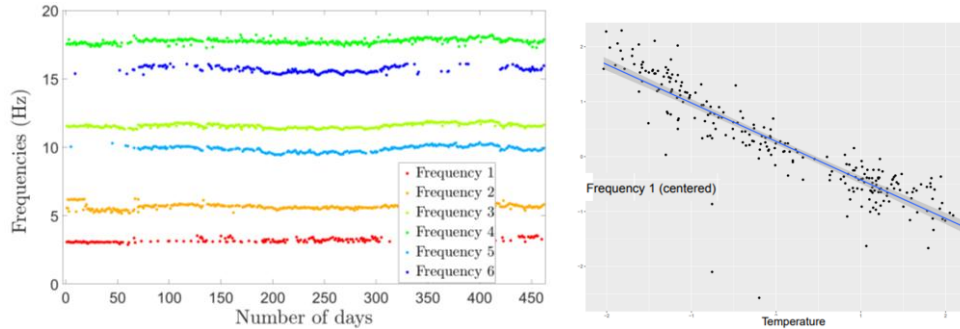


Figure 11. Daily natural frequencies of bridge pier P4 over 1.5 years and example of temperature correlation.

As a first attempt to correlate natural frequencies and hydraulics, Figure 12 compares the first frequency with water level changes (data are centered and normalized). Some variations are due to an added mass effect on the structure when the water level increases but no clear correlation is observed. Further research is needed to establish a reliable scour assessment by comparing data to bathymetry evolution.

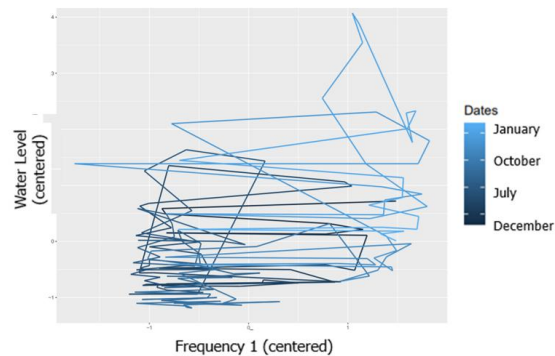


Figure 12. Evolution of the first frequency with water level changes.

CONCLUSION AND PERSPECTIVES

The two presented experiences of field instrumentation for continuous scouring monitoring, demonstrated the feasibility of complete instrumentation for scour monitoring. Such instrumentation needs to be properly prepared and checked before the installation and it is important to be able to monitor the installation and intervene in the event of damage to the device. The possibility of having a robust and in-depth analysis of the data was also showed. It allows, in particular, the monitoring of scour and characteristic flow data. More studies and work are still needed to reduce to optimise the cost of such instrumentation and their automation.

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