In Situ Measurements and Mitigations of Nappe Oscillations – the Papignies and Nisramont Dams in Belgium

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In Situ Measurements and Mitigations of Nappe Oscillations – The Papignies and Nisramont Dams in Belgium

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\textbf{Abstract:} Although good practices in flap gate design recommend adding splitters on the crest to provide sufficient nappe aeration and, thus, prevent nappe oscillations, oscillations problems have been detected on the flap gates of the recently commissioned Papignies weir on the Dendre River in Belgium. These oscillations were causing vibrations of the actuators, which could lead to malfunctioning. In addition, they were generating noise, which is a nuisance for people living nearby. Similar problems were reported for the downstream lift gates of the Nisramont weir on the Ourthe River, also in Belgium. In this context, the paper presents field measurements performed first to define the range of upstream heads prone to cause downstream nappe oscillations and, second, to quantify the effectiveness of additional splitters to mitigate the problem. Measurements with monoaxial accelerometers, microphone, cameras (including a high speed one), and an ultrasonic water level sensor were performed and compared. Data analysis shows a clear correlation between sound, image, and accelerations dominant frequencies. Results demonstrate the effectiveness of adding an extra splitter between each existing splitter in order to avoid the occurrence of nappe oscillations. These in situ measurements validate results from experimental tests performed at the Liege University on a large scaled model of a free surface weir aiming at determining the maximum spacing of splitters to avoid nappe oscillations.

\textbf{Keywords:} nappe oscillations, flap gates, in situ measurements

\section{Introduction}

Identified as undesirable and potentially dangerous, nappe oscillations can occur on free-overfall structures operating under low head conditions (Naudascher and Rockwell, 1994). This phenomenon is characterized by oscillations in the thin flow nappe cascading downstream of weirs, gates or, fountains. These oscillations may induce significant vibrations in the structures and mechanisms as reported in the case of Linville Land Harbor Dam rehabilitation (Crookston et al., 2014). They also produce a significant level of noise described as sounding similar to a helicopter or an amplified bass note (Casperson, 1993).

In the case of flow over a gate, the occurrence of the phenomenon has been attributed in part to the interaction between the flow and the enclosed air pocket between the gate and the nappe (Naudascher and Rockwell, 1994). In fact, the setup of splitters to the gate crest in order to divide the water falling sheet and aerate the air pocket has proven to be an effective mitigation technique and has become a common mitigation technique in gate designs (Lodomez et al., 2016; Naudascher and Rockwell, 1994; Sumi and Nakajima 1990; USBR, 1964). However, vented nappe does not necessarily prevent the oscillation occurrence in case of free surface weir (Binnie, 1972; Crookston et al., 2014; Lodomez et al., 2018), as depicted in this paper involving the Papignies flap gate.

Over the last 60 years of research, three factors have been pointed out to be the possible source of nappe oscillations: the instability of the nappe itself, the fluctuation of air pressure behind the nappe, and the structure acting as a vibrating system (Sato et al., 2007). Although many researchers focused on the behavior of a thin sheet of water flowing vertically (Binnie, 1974; Casperson, 1993, 1994; Girfoglio et al., 2017; De Luca, 1997; De Rosa et al., 2014; Schmid and Henningson, 2002), the cause of the phenomenon is still unclear.

New experimental investigations were undertaken recently at the Engineering Hydraulics Laboratory of the University of Liege on a 1:1 physical model of free surface linear weir with the aim of getting data in real size chute conditions for dam emergency structures prone to nappe oscillations. Based on this physical model, Lodomez et al. (2017) studied the occurrence of nappe oscillations for an unconfined flow nappe and proved that the flow range affected by nappe oscillations reduces according to the decrease of the crest width.
Recently, nappe oscillations have been observed on Belgium dams during low-flow periods on the Nisramont gates and after three months of operation of the Papignies weir, despite the nappe aeration by splitters. Using the characterization methods presented in Lodomez et al. (2018), in situ measurements were performed in collaboration with the Service Public de Wallonie (DGO2) to define the range of upstream heads prone to cause nappe oscillations and to quantify the effectiveness of additional splitters to mitigate the problem. This paper presents the results of these in situ measurement campaigns.

2. Papignies and Nisramont Dams

Papignies dam (Figure 1) is a water level regulating structure on River Dendre (Belgium) in operation since August 2016. The dam consists of two flap gates 3.885 m high and 8 m wide. Each gate is operated through an actuator asymmetrically placed on the central pile. As illustrated in Figure 2, the gate is a thin sheet of metal (15 mm thick) reinforced by a beam structure on the downstream face. Torsional rigidity is provided by a cylinder 0.813 m in diameter at the gate basis. The gate crest is equipped with splitters every 1.65 m. The width of these splitters varies from 40 mm at the connection with the gate to 100 mm at the free extremity (Figure 2). The mean of the upstream water level is 23.65 m DNG (Belgian altitude reference system) while the downstream one is 21.20 m DNG, which give a mean of the fall height of 2.45 m.

![Figure 1. Papignies dam: a. View from upstream, b. View from downstream](image1)

Nisramont dam (Figure 3) was built in 1958 on the River Ourthe to create a $3.10^6$ m$^3$ reservoir intended for drinking water supply. The spillway is controlled by three down lift gates that can be lowered being a concrete weir. Each gate is 12.5 m wide and 3 m high. The gate crest is profiled like an arc to complete an ogee profile when the gate is lowered below the concrete weir. There is no splitter on the gate crest as illustrated in Figure 3c. The gates are actuated on both extremities with symmetrical cables and pulleys. Nappe oscillation risk was well known by local operators. They managed uneven position of gates in order to avoid occurrence of these oscillations. When the regulation system of the dam was upgraded 5 years ago, the three gates were set to operate at the same level. As a result, low and medium discharges are now equally distributed among the gates and the nappe thickness is reduced. Nappe oscillation occurrence sharply increased with this new operational set-up. This observation justified the in situ measurement campaign and the design of splitters.

![Figure 2. Papignies flap gate: a. View from downstream, b. Details of the gates, dimension in mm](image2)
3. Instrumentation and Methodology of in Situ Measurements

To assess the occurrence of nappe oscillations and to characterize them, three types of devices were used during both in situ measurement campaigns. To collect data on structure acceleration, noise production, and visible oscillations of the nappe, a set of accelerometers, a microphone, and a high speed camera were used. Simultaneously, the hydraulic characteristics of the flow were monitored. The gates being identical on each dam, only one of them was instrumented.

In Papignies, the in situ measurements were performed in two phases (Bousmar and Libert, 2017). The first one considered the exiting configuration (Figure 2). Then, additional splitters were added as illustrated in Figure 4. They were 50 mm wide, 125 mm high, and decreased the existing splitters spacing from 1.65 m to 0.825 m. The measurement methodologies were identical for both configurations as described in the following. To investigate the range of upstream heads that generates oscillations, the gate was operated to get heads between 8 mm and 74 mm for the existing configuration while a range between 19 mm and 103 mm has been tested for the configuration with additional splitters.

In Nisramont, a first measurement campaign focused on the vibrations of the gate, using only accelerometers (Bousmar and Libert, 2015). Three configurations were tested: without splitters, with temporary splitters spaced 0.95 m apart (Figure 4c), and with temporary splitters spaced 1.95 m apart. The temporary splitters were 50 mm wide and 150 mm high. Flow conditions covered upstream heads between 25 mm and 230 mm. Acoustic and video investigations were performed during a second campaign. During this second campaign, only the gate without splitter was tested for upstream heads between 60 mm and 180 mm.

3.1. Hydraulic Characteristics

The upstream and downstream water levels and the actuator/gate crest position were monitored and provided the head at the crest. In addition, an ultrasound distance sensor was added to verify the upstream head measure during the tests. For each test, measurements were performed during 2 minutes with a rate of 1 kHz in Papignies, while a rate of 500 Hz and a duration of 1 minute were considered in Nisramont.
3.2. Oscillations Characteristics

3.2.1. Accelerometers

In Papignies, two types of monoaxial accelerometers were positioned at the connection between the actuator and the gate: piezoelectric sensors PCB 393B12 (range 0.5g) and capacitive sensors PCB 3701D1 (range 3g). Three sensors of each type were used to obtain data according to the three axes as displayed in the Figure 5. Measurements were performed during 2 minutes with a rate of 1 kHz. Regarding nappe oscillations, the analysis focused on the standard deviation of the accelerometer measurements representative of the oscillation intensity around the mean value and on the acceleration spectrum that enables to differentiate periodic vibrations at a clearly identified frequency from a high level noise with no dominant frequency.

![Figure 5. Set of accelerometers: a. Papignies, b. Nisramont.](image)

In Nisramont, monoaxial accelerometers (PCB 393B12) and velocimeters (Syscom MS2003+) were positioned on both sides of the gate, at the connection between the pulleys and the gate. Accelerations and velocities were recorded along the vertical and the longitudinal (normal to the gate) axes.

3.2.2. Sound Measurement

To get data on the noise produced by the oscillations, a free-field microphone MC212 was placed in front of the nappe on a bridge at Papignies dam and on the downstream right bank of the stilling basin at Nisramont dam. The microphone had a frequency range between 6 Hz and 20 kHz, and a dynamic range between 15 dB and 146 dB. The recording and analysis of audio data were carried out by means of the SYMPHONIE software suite.

As reported in Lodomez et al. (2018), the sound analysis supplies the mean auto-spectrum of the audio signal, which is representative of the sound level for each frequency of the noise. The mean auto-spectra are typically of two types (Figure 6a). In case of nappe oscillations, the mean auto-spectrum presents a clearly visible peak in sound level, while there is no obvious dominant peak if there is no oscillation. Therefore, the sound analysis supports the detection of the oscillations and provides, in case of nappe oscillation occurrence, the two associated parameters: magnitude of the noise and its associated frequency.

3.2.3. Flow Visualization

Another method used to characterize the nappe oscillations is based on image analysis. Horizontal bands/waves are detectable in the flowing nappe in case of nappe oscillations as illustrated in Figure 6b. The flow visualization was performed with a Go-Pro Hero 4 camera (acquisition rate of 240 Hz) placed in front of the falling nappe. Assuming that the horizontal bands are due to the lighting on the undulating surface, the frequency of the horizontal bands is determined by the Fast Fourier Transform of the time evolution of data carried by a set of pixels on a succession of images. Details of this method are provided in Lodomez et al. (2018).
4. Results

4.1. Occurrence of Nappe Oscillations for the Existing Configuration

4.1.1. Papignies Dam

Based on acceleration measurements, noise analysis, and flow visualization results, nappe oscillations were detected for upstream heads between 20 mm and 40 mm for the existing configuration. In this range of head, the standard deviation of the acceleration increases significantly and leaves the linear trend as illustrated in Figure 7. This figure illustrates these increases in acceleration for both types of accelerometer, especially in the y-direction. In addition, the maximum sound level of the mean auto-spectrum exceeds 70 dB (Figure 7) and is associated with a dominant peak. Horizontal bands are also visible for upstream heads between 20 mm and 40 mm as illustrated in Figure 8. For lower heads, some oscillations are visible. However, the nappe breaks before impact and the intensity of the acceleration and noise generated are not strong.

The frequencies associated with the noise and horizontal bands are between 21 Hz and 23 Hz. As already observed in Lodomez et al. (2018), sound and image analyses give, for a given head, the same frequency of oscillation (to the uncertainty of the measurements). In the present measurements, it was additionally possible to confirm that these dominant frequencies are coherent with the spectrum obtained from the gate vibration measurements. As an example, Figure 9 shows an oscillation spectrum for a head of 30 mm. A significant peak is observed around 23 Hz. Secondary lower peaks are observed around 14 Hz and 21 Hz, while additional large peaks are observed for higher frequency harmonics.

Figure 6. a. Two types of mean auto-spectrum of sound recording and b. Visualization of the nappe oscillations through the horizontal bands in Nisramont dam.

Figure 7. Papignies: Standard deviation of acceleration measurement according to x, y and z, a. for piezoelectric accelerometer and b. for capacitive accelerometer, and maximum sound level of the mean auto-spectrum.
4.1.2. Nisramont Dam

Based on vibration measurements and flow visualization results, nappe oscillations were detected for upstream heads between 50 mm and 230 mm, in the case of the existing configuration. Horizontal bands are clearly visible for upstream heads between 50 mm and 125 mm as illustrated in Figure 10. For upstream heads lower than 30 mm, the thin sheets of water are broken. First, horizontal bands are visible, especially in the bottom of the nappe, for an upstream head of 50 mm. As the upstream head increases, these horizontal bands developed more as illustrated for an upstream head of 100 mm in Figure 10. Finally, from visual observations, the bands tend to decrease for the upstream head higher than 125 mm.

However, severe vibrations were still recorded on upstream heads as high as 230 mm. As an illustration of these vibrations, Figure 11a shows the amplitude of the horizontal acceleration. A local minimum of the acceleration is observed for upstream heads around 125 mm, corresponding to the vanishing of the visible horizontal bands. Then, for higher heads, vibrations increase again. The analysis of the vibration spectrum (Figure 11b) shows that the energy of the vibrations for these higher heads is concentrated at frequencies between 14 and 20 Hz. This clear peak in the spectrum denotes a periodic phenomenon, even if it is at this stage not clear if this is still a nappe oscillation or another kind of flow/structure instability.

Regarding the sound measurements, a dominant peak was detected in the mean auto-spectrum for upstream head between 60 mm and 180 mm. Image analysis also highlights a dominant peak for upstream head up to 180 mm. The frequencies associated to these vibrations are reported in Figure 12 and compared to the frequencies of the acceleration signals and image analysis. This figure shows that the frequencies are identical whatever the measurement techniques and even if measurements were not recorded during the same test campaign. It also illustrates a decrease of the frequency from 35 Hz to 14 Hz for an increasing upstream head. Lastly, it confirms that the vibrations recorded for heads larger than 125 mm are also due to nappe oscillation.
Figure 10. Nisramont: Flow visualisation for an upstream head of (a) 26 mm; (b) 51 mm; (c) 105 mm; (d) 124 mm

Figure 11. Nisramont, acceleration in the longitudinal axis: a. standard deviation and b. spectrum

Figure 12. Nisramont: Frequencies from sound, image and velocities analyses
4.2. Efficiency of Additional Splitters

4.2.1. Papignies Dam

The addition of splitters between each existing water breaker prevents the occurrence of nappe oscillation as illustrated in Figure 13. For the whole range of upstream heads tested, this figure shows no increase of the standard deviation of the acceleration and a maximum sound level below 70 dB. In addition, horizontal bands are not visible as illustrated in Figure 14b for upstream heads that initially generated oscillations. However, in case of lower upstream heads, nappe oscillations are still visible but don’t generate significant noise or acceleration on the actuator.

![Figure 13](image1.png)

**Figure 13.** Papignies: Impact of additional splitters on a. the standard deviation of acceleration measurement according to x, y and z (for piezoelectric accelerometer) and b. the maximum sound level of the mean auto-spectrum.

![Figure 14](image2.png)

**Figure 14.** Papignies: Flow visualisation of the flowing nappe for an upstream head of: a. 18 mm and b. 35 mm, for the configuration with additional splitters.

4.2.2. Nisramont Dam

The addition of splitters with a spacing of 0.95 m avoids the occurrence of nuisance due to nappe oscillations as illustrated by the acceleration measurements in Figure 15. Some horizontal bands are still observed visually for the lower upstream heads but do not generate significant noise or vibration.

When increasing the spacing of splitters to 1.95 m, the nappe oscillations were more perceptible. For upstream heads between 40 and 70 mm, significant vibrations were observed as depicted in Figure 15. Accordingly, it was recommended to fix the spacing of the splitters to be installed at 0.95 m.
Figure 15. Nisramont: Impact of additional splitters on the standard deviation of longitudinal acceleration measurement

4.3. Maximum Spacing and Affected Upstream Heads

All these findings are in line with the experiments made on a “prototype scale” model at the Engineering Hydraulics Laboratory of the University of Liege. Indeed, Lodomez et al. (2017) showed that nappe oscillations decrease with the decreasing weir width and tend to disappear for widths lower than 1 m. The study also showed that the flow range (or upstream head) affected by the nappe oscillation decreases with the width. For a crest 3.45 m wide with a quarter round profile, the upstream heads affected by oscillations are between 17 mm and 50 mm, while for a crest 1.45 m wide, the upstream head range is reduced between 17 mm and 30 mm. The same tendency was observed on Nisramont dam. Nappe oscillations are observed for upstream heads between 40 mm and 70 mm using 1.95 m spaced splitters, while they are observed for upstream heads between 50 mm and 230 mm without splitter.

5. Conclusions

In situ measurements were performed on two Belgium dams subjected to nappe oscillations under low head conditions. These measurements illustrated the reproducibility of the phenomenon observation, independently of the measurement techniques used to characterize the oscillations, i.e., accelerometers, velocimeters, microphone, and high speed camera. In particular, oscillations frequencies were identical whatever the measurement technique and the time of the measurements.

In addition, the tests showed the effectiveness of splitters spaced less than 1 m to prevent nappe oscillations. They also indicated that a too large splitter spacing does not prevent nappe oscillations and that the range of upstream heads prone to induce oscillations reduces with the free crest width, i.e., with the splitters spacing.

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7. References


