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Nappe Vibration Mitigation Techniques for Free-overfall Structures

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ABSTRACT

Nappe vibration is a phenomenon that has been witnessed in the field for a variety of different free-overflow hydraulic structures operating at low heads, such as fountains, crest gates, and weirs. This phenomenon is visually characterized by oscillations in the thin nappe cascading downstream of the control structure. These oscillations can produce a significant level of noise and acoustic pressure waves, which can increase the environmental and societal impacts of the hydraulic structure. As a result, a detailed investigation has been undertaken to identify practical and effective mitigation solutions for free-overfall structures where nappe vibration may be of concern. Research is being performed with a prototype-scale linear weir (weir length of 3.5 m and fall height of 3 m) located at the Engineering Hydraulics laboratory of the University of Liège to assess the effectiveness of various crest modifications and any corresponding impacts to hydraulic efficiency (i.e., flow rate). The test matrix includes the optimization (position and spacing of elements) of three mitigation solutions, which are projecting bolts, deflectors, and step. In addition, a high-speed camera and audio equipment have been used to evaluate effectiveness of the configurations in reducing nappe vibration. Finally, this practical study has identified countermeasures that are suitable for retrofits and new construction, easy to construct, durable, hydraulically efficient, and that have minimal potential for debris collection.

Keywords: *Spillway, nappe vibration, nappe oscillations, physical modelling, flow acoustics.*

1. INTRODUCTION

Nappe vibrations have been identified as an undesirable and potentially dangerous phenomenon in the case of flow over a gate (Naudascher and Rockwell 1994; USBR 1964). The occurrence of nappe vibration on this widespread type of structure 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). Indeed, adding splitters to the gate crest to divide the nappe, thus venting the air pocket, has been successful in mitigating nappe vibration problems in some instances.
In addition to gates, nappe vibrations have also been observed on free surface weirs, including labyrinth weirs, even with an aerated air pocket behind the nappe (Crookston et al. 2014; Crookston and Tullis 2012; Metropolitan water and board 1980; Schwartz 1966). However, such dam safety structures typically operate less frequently than overflow gates, which are usually used as regulating structures and, therefore, operate regularly. As a consequence of this lack of documentation for operating conditions, the low number of free surface weirs leading to nappe vibration has promoted the implementation of case-by-case countermeasures, such as an increase in the crest roughness or a modification of the crest profile (Metropolitan water and board 1980).

Beside these practical considerations, a review of the scientific literature shows that over the last 80 years, a lack of consensus exists on the causes and source of the oscillations or vibration development (Charles Knisely personal communications 2015). The most commonly suggested theory behind the mechanism is based on Kelvin-Helmholtz instabilities at the interface between falling water and air (Casperson 1993), with a source of the vibrations distributed along the nappe. However, this theory requires an appreciable velocity differential between the air and the falling water, which is likely not reached at the crest. Others point to the pressure discontinuity at the weir crest as the cause of the phenomenon (Chanson 1996), with an origin of the vibrations at the crest. The resonance with the air pocket entrapped behind the nappe is, in that case, described as a cause of amplification of nappes oscillation (Naudascher and Rockwell 1994). Twenty years after these early works, following the nappe vibration problems experienced after the rehabilitation of the Linville Land Harbor Dam, new investigations were conducted at the Utah Water Research Laboratory (Utah State University) (Anderson 2014; Crookston et al. 2014). They suggest that the initiation of the instability most likely occurs at the weir crest. Indeed, the waves resulting in the vibrations are observed directly after the flow separation from the weir crest (even for unconfined nappe models), and the roughness modification of the weir affects the vibration. In addition to these results, significant scale effects have been shown to affect the phenomenon, especially on the function of the air pocket entrapped behind the nappe. It can be concluded from literature that this is a complex hydraulic behavior where more than one mechanism might initiate vibration, provide feedback, and/or sustain the vibration, with an enclosed air cavity serving as an amplifier and not as an absolute requisite attribute for occurrence (Rockwell and Knisely 1979; Sato et al. 2007).

The current experimental study was undertaken to develop generic scientific conclusions regarding the physical processes and, especially, appropriate mitigation techniques by means of an experimental study on a large-scale model, including a means of quantifying the vibrations and the level of mitigation provided by crest modifications. This paper provides an overview of the preliminary results regarding the mitigations techniques.

2. EXPERIMENTAL SETUP

The experimental apparatus used in this study is located at the Engineering Hydraulics laboratory of the Université de Liège. It is illustrated in Figure 1. This large-scale model is a confined prototype-scale linear weir with a 3.46-m long crest and a 3.04-m high chute. The fall of water from the weir is confined between two lateral walls and a back wall, one lateral confinement wall being transparent (Plexiglas) and the others black multiplex panels.

Figure 1. Prototype-scale model

Flow is supplied to the model via two pipes, as shown in Figure 2, which are connected to two regulated pumps. Flows enter through perforated pipes parallel to the crest, which are located on the bottom of the reservoir. The maximum unit discharge is 7.22×10^{-2} m²/s (250 l/s in the model). The discharge is measured with an electromagnetic flow meter located in the supply piping (accuracy of 0.5% FS). In the reservoir, a baffle wall of synthetic membranes further assists in providing flow velocities as uniform as possible upstream of the crest (Figure 2).

The weir crest is a 15-cm radius quarter-round followed by a flat 15-cm long horizontal element. This geometry is patterned after typical prototype dimensions of reinforced concrete weirs. The goal of the study being to identify suitable mitigation solutions to nappe vibrations, three types of crest modifications, i.e., projecting bolts, deflectors, and step, were tested as illustrated and listed in Table 1.

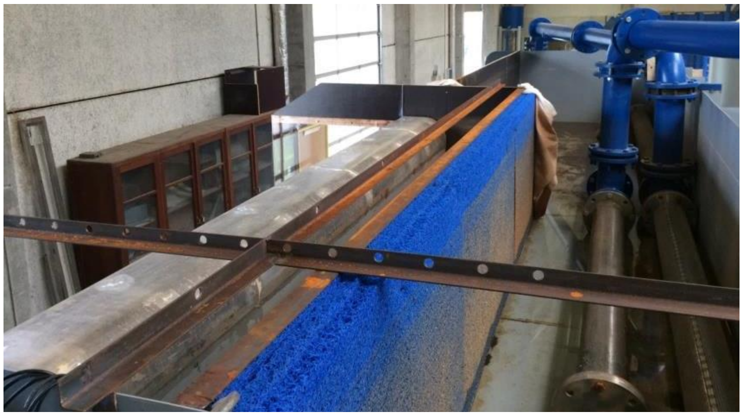


Figure 2. View of the reservoir, water supply pipes, and the baffle wall

The following equipment is used in the experiments for data acquisition:

- high-speed video camera to capture images of the falling water. The camera records 240 frames per second,
- microphone in front of the falling nappe to characterize the nappe vibration phenomenon in terms of sound peak frequency following a Fourier transform of the audio signal.

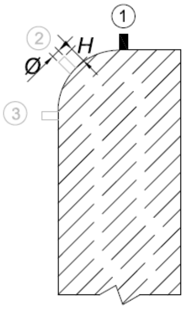
3. RESULTS AND DISCUSSION

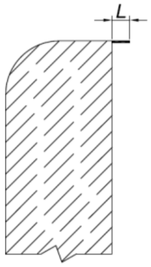
3.1. Base Configuration Analysis

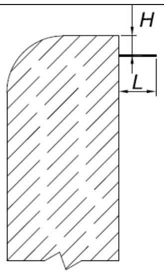
A preliminary study has been conducted on the non-modified quarter-round crest to establish the flow range that induces nappe vibrations and to characterize nappe vibration acoustics. This characterization is based on acoustic measurements and flow visualization. Audio and image recordings with a microphone and a high-speed camera (240 fps) have been made for various flow rates. A Fourier transform has been applied to the acoustic signal in order to isolate the dominant frequencies, and the lens distortion of the extracted images has been corrected. High-speed camera images in combination with Fourier transform of sound recording are illustrated in Figure 3 for a range of unit discharges.

For unit discharges between 0.01 m²/s and 0.07 m²/s, measurements give a dominant frequency that varies between 30.75 Hz and 35.5 Hz. The associated sound level reported as a function of the discharge in Figure 4, combined with the visualization of nodal lines, allowed researchers to detect nappe vibration regions. Three distinct areas can be observed and distinguished from a hypothetical behavior without vibration (dashed line). Indeed, a significant increase of the sound level that exceeds 80 decibels (the mean sound level) occurs as the discharge increases up to 0.025 m²/s. Then, the sound level remains steady in the range of 100 dB for discharges ranging from 0.025 m²/s to 0.045 m²/s. Finally, as the nappe oscillation visually disappears, the sound level decreases and tends to stabilize at 80 dB. This base configuration analysis documents a baseline range of nappe vibration for unit discharges between 0.015 m²/s to 0.05 m²/s.

Table 1. List of mitigation techniques

PROJECTING BOLTS					
	N°	Characteristics (cm)			
		Diameter, Ø	Height, *H*	Spacing, *s*	Position
	PB1	2	1.5	10	1
	PB2		2.5		
	PB3		3.5		
	PB4		4		
	PB5		2.5	20	
	PB6		4		
	PB7		4	40	
	PB8		4	80	
3 possible positions of bolts as represented.	PB9		4	10	2
	PB10		8	20	
	PB11		4	20	3
	PB12		8		

DEFLECTORS				
	N°	Characteristics (cm)		
		Length, *L*	Width, *W*	Spacing, *s*
	D1	5	50	100-200
	D2	10		
	D3	15		
	D4	5	20	20
	D5	5	30	30

STEP				
	N°	Characteristics (cm)		
		Length, *L*	Height, *H*	Width, *W*
	S1	10	5	346

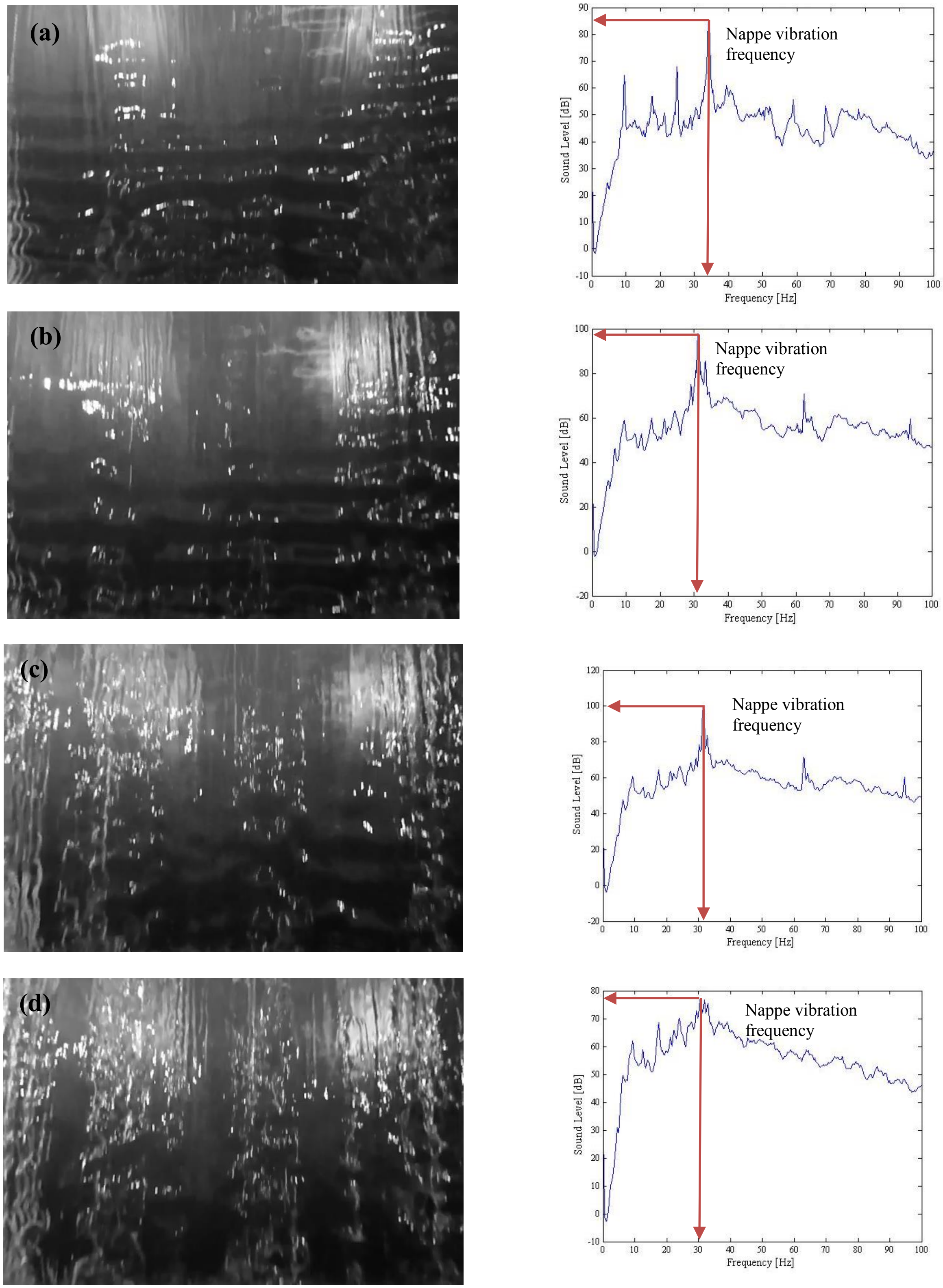


Figure 3. Nappe vibration visualization and associated Fourier transform of sound recording for (a) 0.015 m²/s, (b) 0.03 m²/s, (c) 0.045 m²/s and (d) 0.06 m²/s

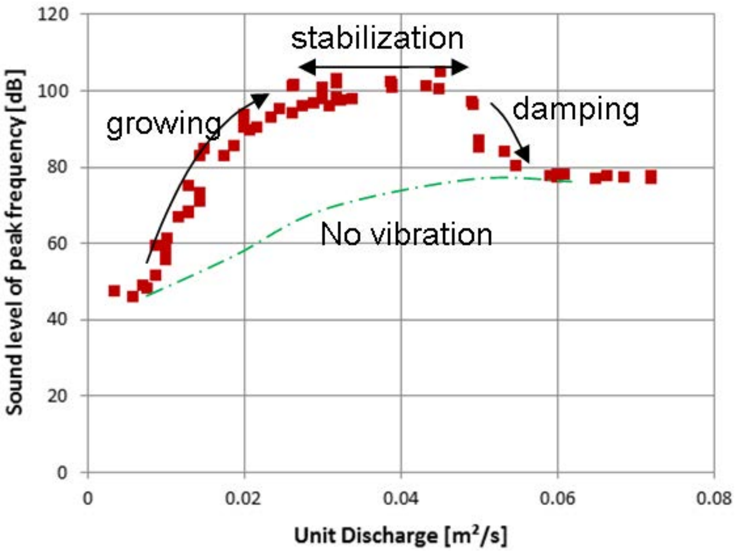


Figure 4. Detection of nappe vibration region using Fourier transform of sound recording

3.2. Mitigation Solutions

As listed in Table 1, the test matrix includes 18 configurations. The mitigation techniques have been tested for the discharges generating the most intense noise disturbances in the case of the smooth quarter-round crest, i.e., 0.03 m²/s, 0.04 m²/s, and 0.05 m²/s. The chronology of these experiments is related to the optimization of the mitigation techniques.

For projecting bolts, the first stage was research into the minimum bolt height required for a specific spacing and position, e.g., 10 cm and position 1 (configurations PB1 to PB4). Then, the bolt spacing was optimized for a fixed bolt height (configurations PB4 to PB8). The results of this first stage of experiments are illustrated in Figure 5 and show that the optimal configuration of projecting bolts is the configuration PB 6. Finally, in order to reduce the potential for debris collection, two additional positions (2 and 3) have been tested and optimized (configurations PB9 to PB12). The results of this second stage of experiments is illustrated in Figure 6; unfortunately, neither position was very effective.

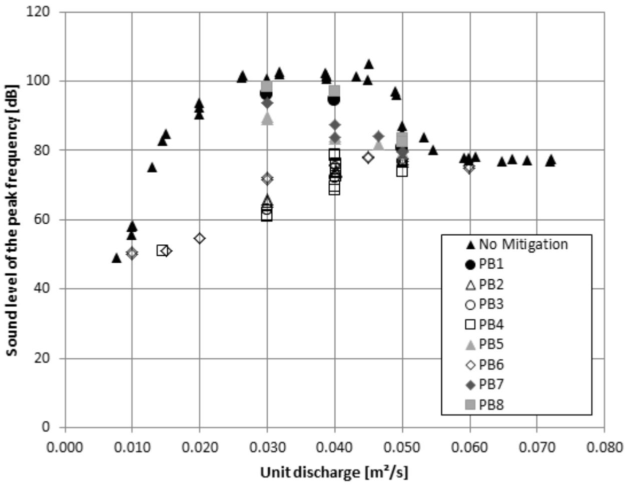


Figure 5. Evolution of sound level at the peak frequency with unit discharge: configurations PB1 to PB8 (projecting bolts mitigation technique)

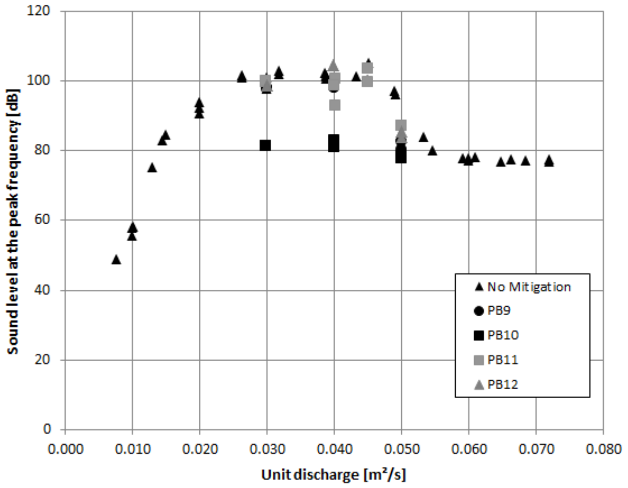


Figure 6. Evolution of sound level at the peak frequency with unit discharge: configurations PB9 to PB12 (projecting bolts mitigation technique)

For deflectors, initial experiments focused on a deflector width of 50 cm located 1 m from the right bank of the weir and 1.96 m from the left bank (configurations D1 to D3). Considering the results gained with a single 50-cm wide deflector as well as the results of the tests for projecting bolts, which concluded that a bolt spacing of 20 cm is necessary to avoid audible nappe vibration, 5 cm long deflectors of 20 cm and 30 cm widths have been tested with a spacing equal to the deflector width (configurations D4 to D5). The results of these experiments are illustrated in Figure 7 and show the effectiveness of configuration D4.

Finally, the results of the experiment for a continuous step along the entire length of the weir and a minimum length of the step (determined from the trajectory of the nappe in the case of smooth crest) are illustrated in Figure 7. This mitigation technique was found to be effective and would likely be a preferred approach for field installations.

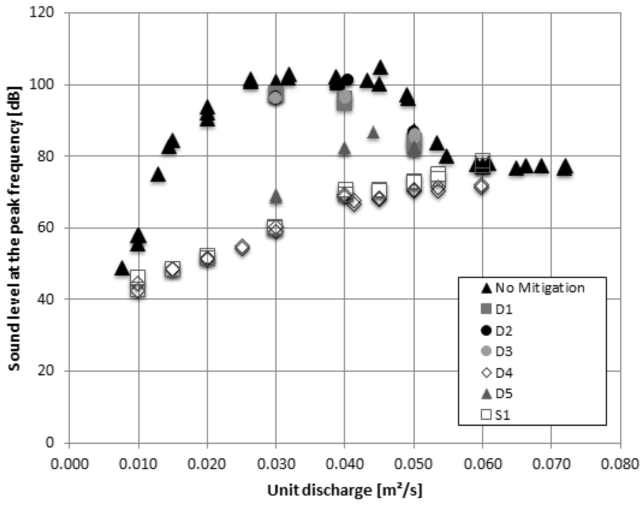


Figure 7. Evolution of sound level at the peak frequency with unit discharge: configurations D1 to S1 (deflectors and step mitigation techniques)

3 CONCLUSIONS

The primary goal of this study was to develop practical countermeasures for nappe vibration that are suitable for retrofits and new construction, easy to construct, durable, hydraulically efficient, and have minimal potential for debris collection. In the current experimental study, three mitigations techniques have been tested and turned out to be effective. Indeed, if the nappe dividing does not exceed 20 cm for projecting bolt and deflectors, the nappe dividing led to a significant decrease of sound level frequency peak. Foremost, the optimization procedure shows that the spacing length required for projection bolts and deflectors is a fundamental parameter and leads to optimal configuration PB6 and D4. Nappe visualization of these optimal configurations still displays nappe oscillations, which are yet phase shifted. Also, the efficiency of the step, as well as the optimal position of the projection bolt (position 1), indicates the sensitivity of the nappe vibration phenomenon to turbulence and upstream hydrodynamic conditions.

A step placed along the whole crest that modifies the flow conditions also proves to be effective and easy to construct since the length of the step is the sole setting. In contrast, projecting bolts, which require the choice of diameter, spacing and, transversal position, seem to be the least suitable solution. The findings of this study should be of interest to owners, operators, practitioners, and researchers involved with free-overfall hydraulic structures.

4 ACKNOWLEDGMENTS

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