Mitigation Investigation of Flow-induced Vibrations at a Rehabilitated Spillway

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Abstract: Linville Land Harbor Dam was recently rehabilitated and provided with a labyrinth spillway to increase flood passage capacity. Nappe vibration, a condition that can occur at hydraulic structures with a free overfall, has been observed for low flows. The associated noise affects a private residence in close proximity to the spillway. As a result, a detailed investigation has been undertaken at the Utah Water Research Laboratory that uses physical modelling (linear weirs) to study mitigation options. Nappe vibration for a fully vented nappe has been observed in the laboratory. Preliminary results indicate that nappe breakers are a less desirable mitigation option due to spacing requirements. Adding roughness to the crest is highly effective as it increases turbulence, perturbs the laminar boundary layer, decreases nappe uniformity, and alters the flow characteristics where the nappe impacts the tailwater.

Keywords: Spillway, labyrinth, nappe, vibration, acoustics, physical modelling.

1. INTRODUCTION

1.1. Spillway Rehabilitation with Passive Control Structures

The rehabilitation of existing dams is an issue for many countries today. Aging water infrastructure is in need of maintenance, repair, and upgrading. Due to population growth and to advances in scientific understanding and technology, the emphasis on dam safety and the requirements for reliable spillway operation continue to increase. As a result, many dams are in need of rehabilitation to comply with stricter dam safety criteria.

Passive control spillways are often a preferred option for rehabilitation because no personnel or automated systems are required to operate the spillway. Reliability is increased since the potential of a gate malfunction, an automated system failure, or an operator who is unable to reach the dam during a flood is eliminated. A linear weir (i.e., sharp, ogee, broad-crested) is a common passive control spillway and the weir length is the most influential factor regarding discharge capacity. Because many upgrades are motivated from inadequate spillway capacity, non-linear weirs are a particularly effective solution for rehabilitation. Common types of non-linear weirs include labyrinth weirs (Crookston & Tullis 2013a), piano-key weirs (Erićicum et al 2013), and box-inlet drop spillways (Blaisdell & Donnelly 1966). Non-linear weirs have been constructed at embankment dams, run-ofriver dams, and gravity dams; due to their geometric flexibility, the design of a labyrinth weir is readily adapted to specific project requirements and site conditions.

1.2. Nappe Vibration

Flow over a weir can display a variety of behaviours. For free-flow conditions, the nappe may be clinging, aerated, or drowned. Moreover, it may exhibit dynamic characteristics that vary spatially and temporally. A partially aerated nappe, nappe instability, and nappe vibration (Crookston & Tullis...
behaviours have been observed for labyrinth weirs. Nappe vibration is a condition that can occur for relatively low-head discharges at hydraulic structures with a free overfall, such as weirs, crest gates, and fountains. Nappe vibration is classified in literature as fluid dynamic excitation; vibrations are generated by the fluid and the flow characteristics at the point of detachment and impact are critical (Naudascher & Rockwell 2005).

Nappe vibration can produce horizontal banding on the nappe and undulations are commonly observed (see Figure 1). The most recognizable characteristic of nappe vibration is perhaps the intense acoustic pressure waves and noise (Casperson 1995a) that have been aptly described as sounding similar to a helicopter or an amplified bass note. These pressure waves can reach an intensity where they are readily felt on the skin and have been reportedly heard more than a kilometre from the source (Casperson 1995a).

Several studies have been conducted on nappe vibration. Casperson (1995b) studied undulations that occur on weirs with a curved crest. Schwartz (1966) explored the influence of the boundary layer. One theory for nappe vibration is the Helmholtz mechanism (Helmholtz 1868) that attributes nappe vibration to shear forces that occur between two fluids of different velocities, specifically between the nappe and the surrounding air. An enclosed air pocket behind the nappe (non-vented) can amplify the instability due to said mechanism (Naudascher & Rockwell 2005); however, artificial aeration or venting the nappe does not preclude vibrations from occurring; a fully vented nappe displaying intense vibrations has been observed by Falvey (1980) and studied by Binnie (1972). Although researchers have advanced understanding of nappe vibration, the physical processes of this complex flow behaviour are still unclear.

There is incomplete information regarding effective countermeasures for nappe vibration. One technique applied to a labyrinth spillway in the state of Wisconsin, USA, is nappe breakers or flow splitters at close spacing (approximately 0.6 m to 1 m) (Lux, personal communication, March 26, 2012). The number of flow splitters required for a labyrinth is not trivial, as the weir length of a labyrinth is typically 75 m or more. Additionally, closely spaced splitters can instigate significant debris capture. A second technique that has been applied to prototype spillways is to attach roughness elements along the crest surface, such as with Avon Dam located in Australia (Metropolitan Water, Sewerage and Drainage Board 1980). In the case of Avon, 19-mm diameter crushed stones were glued to the crest. This modification was prompted by a similar but spalled labyrinth crest at Woronora, which had not been observed to display nappe vibration.

The current study was undertaken to further explore nappe vibration, including physical processes and appropriate mitigation techniques. This study was prompted by nappe vibration observed at Linville Land Harbor Dam, which was recently upgraded with a labyrinth spillway. This paper provides an overview of the rehabilitation of Linville Land Harbor Dam and the preliminary results of mitigation modelling via crest modifications.
2. LINVILLE LAND HARBOR DAM

2.1. Background

Linville Land Harbor Dam is located on the Linville River in North Carolina, USA. It is an earth-embankment dam about 10.7 m high that impounds a 19 ha lake. The lake is primarily used for recreation and is a prominent aesthetic feature of the Linville Land Harbor residential community. Several homes in the neighbourhood are in close proximity to the spillway.

The dam was originally built in 1927 and featured an active-control spillway comprised of three tainter gates. Floods in 1940 destroyed the dam, as shown in Figure 2a. The dam was finally reconstructed 30 years later. As part of the 1971 rebuild, two additional gates and an auxiliary spillway (ogee weir) were added (see Figure 2b). In the mid-2000’s, the North Carolina Department of Environmental and Natural Resources, Division of Land Quality, Dam Safety identified this structure as the number one safety hazard in the state. Linville Land Harbor Dam had significantly deteriorated since the 1971 construction, in part due to alkali-silica reaction (ASR) within the concrete mass. Schnabel Engineering was hired in 2007 to design a repair for the dam.

![Figure 2 - Photograph of Linville Land Harbor Dam after 1940 failure (a) and in 2009 after 1971 reconstruction but prior to rehabilitation (b) (photos courtesy of Linville Land Harbor Property Owners Association)]

2.2. Dam Rehabilitation

The most cost-effective rehabilitation alternative identified was to replace the gated primary spillway and auxiliary spillway with a new labyrinth weir. The auxiliary spillway was filled and the labyrinth was constructed in the footprint of the previously gated section. The North Carolina Dam Safety Regulations required that the new spillway safely pass one-half of the probable maximum precipitation (½ PMP) flood event.

The concrete labyrinth spillway, presented in Figure 3, consists of four cycles. Each cycle is 18.75-m deep (upstream to downstream) and 9.14-m wide. The labyrinth has a level crest with a stepped apron; two cycles have a wall height of 4.57 m and the remaining two cycles are taller by 1.2 meters (5.79 m). The 122-m long earthen embankment dam extends from the labyrinth spillway to the right abutment. The reservoir has a normal pool at EL 1,076.67 m, top of labyrinth spillway at EL 1,076.84 m, and top of dam at EL 1,079.6 m.

The Linville River is a designated High Quality Water Trout Stream. To accommodate the trout, a cold water release system was integrated into the design. The cold-water release system contains an upstream and downstream gate (each 1.22-m tall by 0.91-m wide) with a gate bottom elevation of 1,071.07 m. For normal dam operation, the upstream gate is open and allows cold water from the lake to enter the outlet works, while the downstream gate remains closed. Water entering the upstream gate travels vertically through the outlet works and passes over a weir at EL 1,076.67 m.
When both gates are open, the outlet works structure functions as a low-level outlet and can be used to drain the lake. The system is designed to pass flows from 190 l/s to 710 l/s. The elevation difference between the cold water release weir crest and the crest of the labyrinth spillway is 165 mm.

The labyrinth spillway was founded on rock and partially reinforced cast-in-place concrete. Dental and/or cast-in-place concrete was placed as needed on rock to provide a level surface for the labyrinth spillway slabs. A grouting program was conducted in the upstream portion of the labyrinth spillway foundation to create a grout curtain to reduce the potential for seepage through the foundation.

### 2.3. Hydrologic and Hydraulic Analysis

The watershed above Linville Lake Harbor Dam is about 50 square km (19.3 square miles) and ranges in elevation from 1,077 m to 1,812 m. The rainfall data for frequency storms was obtained from “Precipitation-Frequency Atlas of the United States” NOAA Atlas 14, Volume 2, Version 3. The ½ PMP was calculated using the National Weather Service Hydrometeorological Report (HMR) Number 51 and distributed using the HMR-52 computer program. All storms were analyzed with a 24-hour duration.

The runoff was calculated using a USDA-NRCS Runoff Curve Number and Snyder’s Lag time. The watershed model was analysed using the US Army Corps of Engineer’s HEC-1 Flood Hydrograph Package, Version 4.1, and calibrated using annual peak flow stream data from USGS Gauge #02138500, located downstream of the dam.

**Table 1 Results of Hydrologic and Hydraulic Analysis**

<table>
<thead>
<tr>
<th>Event</th>
<th>Rainfall (mm)</th>
<th>Peak Inflow (cms)</th>
<th>Peak Stage EL (m)</th>
<th>Peak Discharge (cms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-year storm</td>
<td>158</td>
<td>88.2</td>
<td>1,077.35</td>
<td>87.1</td>
</tr>
<tr>
<td>25-year storm</td>
<td>192</td>
<td>140.9</td>
<td>1,077.56</td>
<td>139.5</td>
</tr>
<tr>
<td>50-year storm</td>
<td>219</td>
<td>186.6</td>
<td>1,077.68</td>
<td>184.8</td>
</tr>
<tr>
<td>100-year storm</td>
<td>249</td>
<td>239.7</td>
<td>1,077.86</td>
<td>237.4</td>
</tr>
<tr>
<td>½ PMP</td>
<td>462</td>
<td>704.4</td>
<td>1,079.45</td>
<td>693.0</td>
</tr>
</tbody>
</table>
3. NAPPE VIBRATION

3.1. Prototype Observations

Nappe vibration has been observed periodically at Linville Lake Harbor Dam since rehabilitation was completed (Figure 4). The crest is a quarter-ellipse in cross section with a sharp corner on the downstream edge. The concrete work is exceptional; the crest has an extremely smooth, well-shaped and uniform surface. As shown in Figure 3a, a private residence is located just upslope of the left abutment of the dam. The homeowner has stated that when nappe vibration occurs, there are vibrations in the floor and walls of their home and the windows severely rattle. Also, the dishes in cabinets and various decorations and trinkets hanging on the walls were rattling to the point that homeowners removed said items from walls and cabinets.

![Figure 4 - Observed nappe vibration of entire spillway (a) and view of vented vibrating nappe (b) (photos courtesy of Schnabel Engineering)](image)

Flow depths at the crest have been documented by the dam general manager and are summarized in Figure 5; the dashed lines indicate the approximate upper and lower bounds. It is believed that the vibrations occur for flow depths of about 50 mm to 150 mm, although complete measurements outside of this range have not been recorded. Corresponding flow rates for the labyrinth weir are estimated to be from about 2.55 cms to 12.18 cms. For these conditions, the depth of flow on the apron downstream of the labyrinth is relatively shallow. It should be noted that the watershed upstream of dam is heavily wooded; the spillway frequently experiences large woody debris following rain events but the majority of the debris passes over the spillway. The photograph in Figure 4a shows that a portion of the labyrinth was vented by a very large tree trunk that was caught on the spillway crest, yet there was no perceptible reduction in nappe vibration along that sidewall. A preliminary evaluation of sound recorded at the site found the frequency to be approximately 20 to 40 Hz, which is similar to the 48 Hz reported for physical modeling of vibrations for Avon Dam (Metropolitan Water, Sewerage and Drainage Board 1980). Sound recordings of a second labyrinth spillway in North Carolina, USA had similar frequencies but vibrations were only observed for flow depths less than about 100 mm. Physical modelling conducted by Reclamation reported much lower frequencies of about 3.4 to 6.6 Hz (Falvey 1980).
Dynamic monitoring has also been conducted to further investigate the connection between nappe vibration at the dam and the vibrations at the adjacent building (STRAAM 2012). Instrumentation was placed on the labyrinth at two locations, on the left abutment, and within 3 meters of the home. Measurements established the baseline signature of the labyrinth spillway, modal frequencies, and mode shapes. The measured frequencies of the flow were 22 to 25 Hz and 35 to 40 Hz; 40 Hz frequencies were measured in the ground adjacent to and in the walls of the home. However, the structural resonance of the labyrinth spillway was identified at a much lower frequency of about 2 to 6 Hz. Ground motion at the home was horizontal only. No vibrations were observed on the left abutment. It was concluded that the vibrations are primarily transmitted acoustically [Charney, personal communication Feb. 2012] Dr. Charney of Virginia Tech, subcontracted by STRAAM, Inc., a structural vibrations expert. It is not clear if vibrations are also transmitted through the ground to the home (impact of water on slab transmitted to home foundation) or only through the air to the home and then to the adjacent ground.

3.2. Preliminary Physical Model Results for Mitigation

A detailed investigation of nappe vibration is being conducted at the Utah Water Research Laboratory. The study is focused upon the physical mechanisms of nappe vibration and also various mitigation techniques. The study utilizes two physical models of linear weirs; the smaller weir model is approximately 1.8-m wide, 1.2-m high, and 76-mm thick. The air cavity behind the nappe can be confined or vented to the atmosphere. The larger, prototype-scale model is 4.7-m wide by 3.3-m high with the crest about 0.3-m thick. The larger model utilizes an elevated headbox; there are no walls to confine the nappe as it falls to the floor. The approach flow conditions at the crest, the nappe, and downstream flow conditions are areas of focus. Accelerometers, stroboscope, sound meter, flow transmitter, high definition photographs, and high-speed video recordings are being used in addition to particle imaging velocimetry, dye tracking, flow meters, and point gauges.

Based upon a review of available literature, observations of two prototype labyrinth weirs, and observations in the laboratory, it is hypothesized that nappe vibration can be expressed as:

\[
\text{Nappe Vibration} = f(P, L, V, k, t, p, r, \text{impact})
\]  

where \(P\) is the fall height, or in the case of labyrinth weirs, the weir height; \(L\) is the width of the nappe, \(V\) is the local velocity; \(k\) is the turbulent kinetic energy per unit mass; \(t\) is the thickness of the nappe, which corresponds to the depth of flow when the location of interest is at the crest; \(p\) is the pressure behind the nappe; \(r\) is the shear force at the nappe surface generated by the jet falling through air, and ‘impact’ denotes the downstream conditions where the nappe impacts the tailwater. Key parameters identified in Eq. (1) provide guidance for nappe vibration countermeasures.

Laboratory observations in the large model with a quarter-round crest shape have documented vibrations occurring for flow depths ranging from about 40 mm to 100 mm (1.5 in to 4 in) and flow rates
from 63 l/s to 180 l/s. Recorded frequencies are about 35 Hz and 16 Hz in the small and large models, respectively. It has been observed that vibrations are amplified by wind and a confined air cavity. Also, vibrations are magnified or attenuated depending upon the angle between the impinging nappe and the downstream apron.

Broad-crest, quarter-round, and half-round crest shapes have been investigated to date. Modifications include flow splitters, a parapet, various groove or notch configurations, and various roughness elements. Vibrations were not observed with the broad-crest shape, likely due to the 90 degree corner at the upstream edge of the weir. As shown in Figures 6 and 7, roughening the crest is highly effective for nappe vibration mitigation. The roughness elements increase turbulence, perturb the laminar boundary layer, and the flow characteristics where the nappe impacts the tailwater have been altered. A splitter spacing of about 1 m was required to reduce vibrations to an acceptable level. Note in Figure 6c that undulations were still observed at this spacing and that the nappe was fully aerated for each configuration presented in Figure 6.

![Figure 6](image)

(a) (b) (c)

Figure 6 - Nappe vibration (a), roughened crest (b), and flow splitters (c) (photos courtesy of UWRL)

![Figure 7](image)

(a) (b)

Figure 7 – Nappe vibration undulations with a smooth quarter-round crest (a) and the same crest with roughness elements that eliminated nappe vibration (b) (photos courtesy of UWRL)

4. SUMMARY AND CONCLUSIONS

Many existing dams are in need of rehabilitation. A labyrinth spillway is a well-established upgrade option; it is a passive-control structure that increases discharge for a given upstream head due to the increase in crest length. Nappe vibration is a flow-induced phenomenon that can occur in hydraulic structures with a free overfall. It produces strong undesirable acoustic pressure waves from the undulations impacting the tailwater and it is rarely reported for labyrinth spillways. Although the focus of previous studies, additional research is needed to advance understanding of this complex flow behaviour.

Linville Land Harbor Dam was recently rehabilitated; the auxiliary spillway and spillway gates were replaced with a labyrinth spillway that features an elliptical crest. The concrete work is excellent with a very smooth and uniform surface. Nappe vibration has been observed for flow depths at the crest between 50 mm and 150 mm; these vibrations affect a private residence in close proximity to the
spillway. The vibration frequency at the spillway and home was observed at about 20 to 40 Hz, which differs from the spillway structural resonance of 2 to 6 Hz.

A detailed investigation is being conducted on nappe vibration at the Utah Water Research Laboratory; a component of this study is focused on crest modifications that eliminate nappe vibration. Preliminary results indicate that nappe breakers are a less desirable mitigation option as a spacing of 1 m or less is required; a large number of nappe breakers would be required for a typical labyrinth spillway and would instigate significant debris capture issues. Applying roughness elements to the crest is highly effective as it increases turbulence, perturbs the laminar boundary layer, decreases nappe uniformity, and alters the flow characteristics where the nappe impacts the tailwater.

5. ACKNOWLEDGMENTS

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6. REFERENCES


