Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 1029-1040

ECCOMAS
Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

ACOUSTIC GUIDED WAVE METHOD TO EVALUATE BLOCAGE IN DRAINS OF DAMS – SMART 2023

A. TARAS[*], M. SOARES[*], M. RODRIGUEZ[*] AND M. ARGOUGES[†]

[*] Hydro Quebec Research Institute (IREQ)
J3X 1S1 Varennes, Québec, Canada
taras.andre@hydroquebec.com

[†] Hydro Quebec Dam & Infrastructures (HQP)
H2Z 1A4 Montreal, Québec, Canada
argouges.matthieu@hydroquebec.com

Abstract. There is a need to reduce the inspection time of drains in dams done through video camera. A method based on acoustic guided wave propagation was developed. A system of loudspeaker and microphone was designed to send and receive at the mouth of drains acoustic waves. Physical models were developed to describe wave attenuation as it propagates and its reflection and transmission through consecutive obstructions. Extensive lab tests were undertaken in 3inch composite and 4inch fibro-cement pipes to evaluate the performances of these models. Wave attenuation coefficient and superposition factor for the recorded reflections were obtained for these two types of pipes. The effects of different pipe conditions were evaluated, such as: distinct and close proximity obstructions, cavity and pipe outlet. Tests were undertaken on actual drains of dams.

Key words: Acoustic wave propagation, guided wave, inspection, drain, pipe, obstruction, blockage, reflection, dam.

1 INTRODUCTION

Drains in dams permit to reduce pressure in cracks by letting the water to seep out of cracks into the drain. However, these drains may with time clog up from calcite deposits. The present camera inspection is tedious and time consuming.

As a faster alternative method, an acoustic system comprised of loudspeaker and microphone was designed to send guided sound waves down the drain and to record their reflections from obstructions. Physical models were developed to describe wave attenuation due to leakage and damping, and to determine reflection and transmission coefficients for multiple obstructions.

The coefficient of reflection, ratio of reflected to incident waves, was correlated to section reduction. Extensive lab tests were undertaken in polyvinyl chloride (PVC) and fibro-cement (FC) pipes to evaluate these models. Wave attenuation coefficients for these two types of pipes were obtained as for the superposition factor for the recorded reflections. The effects of different drain conditions were evaluated, such as: multiple obstructions, cavities.

Peer-review under responsibility of the organizing committee of SMART 2023.
doi: 10.7712/150123.9854.464528

2 TEST SET UP AND INSTRUMENTATION

2.1 Lab test bench

Lab tests were undertaken on straight pipes 21 m in length set on sandbags to attenuate noise, Fig.1. Guided acoustic waves propagations were performed in 10 cm inner diameter FC and 7.6 cm PVC pipes. Sections of pipes with obstructions of different degree were inserted at different positions along the length. A pipe obstruction consisted of putty wall about 2 cm thick filled to a level of the cross-section. The depths were approximately a third of, a half of, three quarters of and a full cross-section.

2.2 Instrumentation

The system to generate acoustic waves and record their reflection was designed with a VISATON model FRS 5 WP loudspeaker and PCB 130A24 microphone. They were inserted ~ 3 cm apart in a widening rubber diameter adaptor attached to a 5cm PVC pipe 30 cm in length, as in Fig. 2. The audio board of the portable computer was used and a LabVIEW application was developed to generate the acoustic signal. The signal from the audio board was boosted through a Lepai amplifier. Reflections coming from obstructions were recorded through the PCB microphone with the XS data acquisition system from Siemens and were analysed using "SimCenter TestLab" software.

Figure 1 10 cm FC and 7.6 cm PVC pipes

Figure 2 Handheld acoustic emitter receiver

2.2 Acoustic measurement process

The source was a loudspeaker that emitted an acoustic sound pressure wave comprised of a single frequency with a train of "n_e" cycles waves which were recorded by the adjacent microphone. The acoustic wave train propagates down the drain and is partly reflected and transmitted when it encounters a partly obstructed section. The delay in time of the reflection is related to the distance travelled from the source. Two different acoustic sound waves were sent into the pipes each with three cycles and wavelength at least 3 times the diameter of the pipes so they were guided: one sound wave with a 30 cm wavelength at a frequency of 1100 Hz, the other wave with a 1 m wavelength at 340 Hz. The wavelength "λ", frequency "f" are related through the sound velocity "v" in air (~340 m/s), such as:

$$v = f \cdot \lambda \tag{1}$$

Two frequencies were selected. The 1100 Hz frequency provided the best reflection to different sizes of obstructions. But the 340 Hz frequency carried further and was less sensitive to elbows. Both frequency wavelengths were chosen to be longer than the diameter for a better guide in the pipe. They were evaluated under lab trials. The measurement sampling rate was 51.2 kHz, the band pass at 20 kHz and an average over 5 signals was applied.

3 PHYSICAL MODEL OF ACOUSTIC WAVE IN AIR FILLED CONDUITS

3.1 Acoustic wave propagation model

Emitted and received wave train "pulses" were characterized by an energy index "E ". This index consisted of the product of the RMS amplitude of the pressure wave pulse in Pascals "P_{rms}" multiplied by the time duration of the pulse "Δt " in seconds over its "n" cycles:

$$E = P_{rms} \cdot \Delta t \tag{2}$$

The acoustic propagational model in pipes is based on the premise that attenuation "α" of the pulse energy "E" that propagates is due to scattering, absorption and leakage through the walls is proportion to the amplitude of the energy:

$$E(x+dx) - E(x) = \alpha \cdot E(x) \cdot dx \tag{3}$$

Solving for (3) produces the following between positions "x_1" and "x_2":

$$E\left(x_2\right) = E\left(x_1\right) \cdot e^{-\alpha \cdot (x_2 - x_1)} \tag{4}$$

Also, reflection and transmission coefficients for obstructions were formulated based on the ratio of reflected "E_r" to incident "E_i" waves at an obstruction and designated as "C_D ":

$$C_D = \frac{E_r}{E_i} \tag{5}$$

This coefficient of reflection was correlated to the degree of obstruction expressed as the ratio "a/A" where "a" is the obstructed area and "A" the total cross section area. The incident and reflected "energies" are values extrapolated from the recorded signals at the microphone to the positions of the obstructions, through expression (4). For the case of several consecutive obstructions a transmission coefficient "C_T" was developed. It represents the ratio of incident to transmitted acoustic pulses at any given obstruction along the pipe as follows:

$$C_T = \frac{E_t}{E_i} = \left(1 - C_D{}^{C_{trans}}\right) \tag{6}$$

The transmissibility power factor "C_{trans}" was obtained through Lab tests.

3.2 Determination of model parameters

The propagational acoustic wave model (4) was modified by incorporating a correction factor "C_{orr}". This factor corrected for the effect of "superposition" only on the incoming reflected pulses. When the reflected pulse comes to the microphone, it overshoots the microphone, "rebounds" on the loudspeaker or the open-ended tube and superposes itself on its trailing part still coming onto the microphone. This happens when the distance between loudspeaker and microphone is smaller than half of the length of the reflection pulse. Expression (4) becomes:

$$E_r\left(x\right) = C_{orr} \cdot C_D \cdot E_0 \cdot e^{-2\cdot\alpha\cdot x} \tag{7}$$

To determine the wave propagation coefficient « α » and "C_{orr}" coefficient for superposition, a series of Lab test were carried out. Using putty, a complete blockage was set at three different distances of 6 m, 10 m, and 13 m, along FC and PVC pipes. With full blockage, it was assumed that the incident wave to the blockage was completely reflected, therefore the reflection coefficient was set equal to one "$C_D = 1$", then (7) was simplified to:

$$E_r\left(x\right) = C_{orr} \cdot E_0 \cdot e^{-2\cdot\alpha\cdot x} \tag{8}$$

Lab tests provided sufficient data to feed a convergence algorithm aiming at establishing the coefficients « α » and « C_{orr} » in (8). Measurements were always taken at the two following frequencies of 1100 Hz (λ = 30 cm) and 340 Hz (λ = 1 m) on each pipe, see Table 1.

The attenuation coefficient for the smaller PVC pipe was roughly 60% of the larger and rougher FC pipe. The superposition was practically inexistent for the 10 cm FC pipe whereas it presented a 30 to 50 % increase for the smaller 7.6 cm PVC pipe. The ratio of loudspeaker diameter to that of the pipe was possibly a factor.

Table 1: Attenuation and superposition coefficients

Pipe	Diameter (cm)	Frequency (Hz)	Attenuation "α"	Factor "C_{orr}"
PVC	7.6	1100	0.026	1.55
PVC	7.6	340	0.016	1.32
FC	10	1100	0.033	1.00
FC	10	340	0.037	1.03

4 PREDISTION OF THE DEGREE OF OBSTRUCTION

The basic premise was that the degree of obstruction "*a/A*" was a function of the coefficient of reflection "C_D".

To establish this relationship, a second series of Lab tests were undertaken whereby the degree of obstruction was varied at each of the three different distances. The correlation had to be independent of distance because the coefficient of reflection was calculated based on the ratio of the reflected and emitted energy values which were extrapolated at the position of obstruction. Correlated functions are presented in Table 2, for the two frequencies and pipes.

Table 2: Correlated functions of *a/A* to C_D

Pipe(cm) Diameter	Frequency (Hz)	Correlated Functions
10	1100	$a/A = 1.05 \cdot C_D - 0.05$
10	340	$a/A = 0.80 \cdot C_D + 0.22$
7.6	1100	$a/A = 1.00 \cdot C_D - 0.01$
7.6	340	$a/A = 0.77 \cdot C_D + 0.27$

The slopes of the correlation function seemed dependent on frequency. The coefficients for attenuation and superposition seemed dependent on diameter and material roughness.

5 CONSECUTIVE OBSTRUCTIONS ALONG A PIPE

Lab tests have shown that it was possible to detect consecutive obstructions over 20 meters. The principle applied was to determine the coefficients of reflection and transmission of a given obstruction before passing to the following one, using expressions (5), (6) and (7). The procedure starts with the first obstruction and ends up at the "mth" obstruction, as follows:

$$C_{Dm} = \frac{E_{rm}}{E_{im}} = \frac{E_{rm0}}{E_0} \cdot e^{+2\cdot\alpha\cdot x_1} \cdot \left\{ \prod_{k=1}^{m-1} e^{+2\cdot\alpha\cdot\Delta_k} \cdot \left[1 - C_{Dk}{}^{C_{trans}}\right]^{-2} \right\} \tag{9}$$

where

C_{Dm} , coefficient de reflection at the mth obstruction

E_0 , acoustic wave energy emitted from loudspeaker

E_{rm0} , reflected wave energy from the mth obstruction recorded at micro

x_i , distance from source to first obstruction

a , coefficient of attenuation : damping, leakage, roughness

Δ_k , distance between obstructions

C_{trans} , transmissibility power factor

5.1 Distinct consecutive obstructions

The case of distinct consecutive obstructions presents itself when two or more consecutive obstructions generate acoustic reflections that show wave trains pulses separated in time, with no overlapping of one onto the other. This happens when the distance "Δ" between two consecutive obstructions is greater than one half of the length of the acoustic wave train pulse of "*n*" cycles coming onto the two obstructions:

$$\Delta > \frac{n \cdot \lambda}{2} \tag{10}$$

5.2 Transmissibility parameter

To be able to predict the degree of obstruction of consecutive obstructions, it was necessary to determine the transmissibility power factor "C_{trans}". It was set as a power in (6) for any degree of obstruction characterized by the reflection coefficient "C_D ".

To determine the factor "C_{trans}", a series of Lab tests were undertaken on each type of pipes. The test procedure was as follows: a first obstruction was set at 6m and a second obstruction placed at 13 m. For a given obstruction at the first position, the degree of obstruction at the second position was varied. As an example, Fig. 3 shows the first wave packet as emitted pulse, the second as the reflected pulse from the 6m obstruction, the third pulse as a multiple reflection of the first obstruction (same time interval as second pulse) and the fourth as the reflected pulse from the second obstruction. The series of measurement provided 16 data (combination of pairs of 4 different obstructions for first and second position). Obstructions ranged from ⅓, ½, ⅔, ¾, to full blockage of the cross-section, Fig. 4. A convergence algorithm was applied to the data to establish the appropriate transmission power factor so to predict correctly the second obstruction. The exercise produced a transmission power factor "C_{trans} = 2.55" for obstructions.

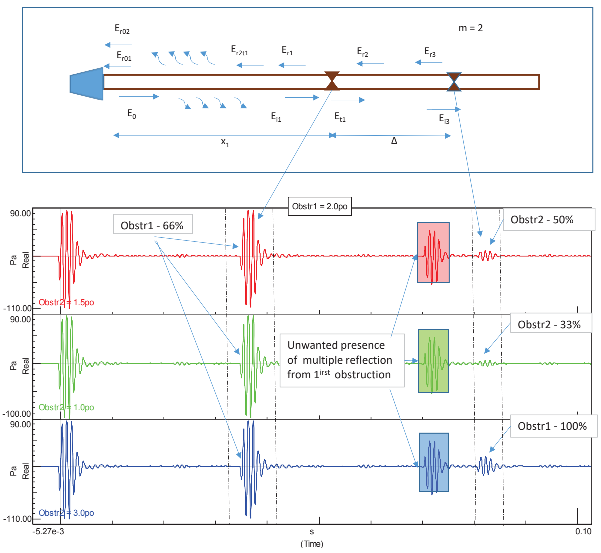

Figure 3 Three tests varying the 2nd obstruction while first kept at 66%

Figure 4 Degrees of obstruction ranging from ⅓, ½, ⅔, ¾ to full section

5.3 Close proximity obstructions

This phenomenon was characterized when a reflected wave train pulse developed more cycles "n_r" than the emitted wave train pulse of "n_e" cycles. This happened when the wave train length is greater than twice the distance between two consecutive obstruction, chapter 5.1, and Fig. 5**.**

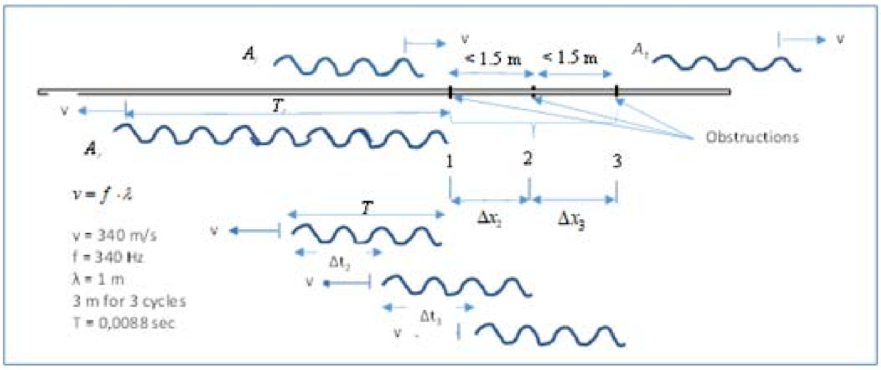

Figure 5 Sketch of a reflection from 3 close proximity obstructions

The string of superpositions of one reflection onto a precedent one depends on the number of obstructions "*m*" in close proximity. The number "*m*" was approximated as:

$$m = ROUNDEDOFFSUPERIOR\left(\frac{n_r}{n_e}\right) \tag{11}$$

The length "*b*" of the zone of close proximity obstructions was evaluated as follows:

$$b = \frac{(n_r - n_e)}{2} \cdot \lambda \tag{12}$$

An approximate model was developed to estimate the degree of obstruction from the reflections of close proximity obstructions. First, a constant distance interval "Δx" was assumed between obstructions. Secondly, an identical apparent coefficient of reflection "C_D" was set equal for each close proximity obstructions. The energy for the reflected wave train "E_r" was computed over its period "T_r" encompassing its "n_r" cycles. Overlap segments of two consecutive reflected pulses were not considered.

The reflected energy "E_r" was equated to the addition of "portions" of the incident energy "E_i" attributed to reflections at each of the "m" obstructions. A reflected "portion" of the incident energy "E_i" was assumed to be function of the transmitted pulse through the first obstruction and of the time interval to travel back and forth between consecutive obstructions. The tail of the last reflection is not overlapped therefore it was considered to retain the period "*T*" of the incident "n_e" wave train pulse. The time interval "Δt" between obstructions was:

$$\Delta t = \frac{2 \cdot b}{v \cdot (m-1)} \tag{13}$$

The time intervals of reflections and the period of the incident pulse should match the period of the close proximity reflection pulse as follows:

$$T_r \approx (m-1)\cdot\Delta t + T \tag{14}$$

The approximate relationship between the incident energy "E_i" and the reflected energy "E_r" of close proximity obstructions was formulated as follows:

$$E_r = \frac{E_i \cdot C_D}{T}\cdot\left\{\sum_{j=1}^{m}\tau(j)\cdot\left[1-C_D{}^{Ctrans}\right]^{2\cdot(j-1)}\cdot e^{-2\cdot\alpha\cdot\left(\frac{b}{m-1}\right)\cdot(j-1)}\right\}, where\_\tau(j) = IF\left(j=m;\tau=T;\tau=\Delta t\right) \tag{15}$$

In expression (15), the only unknown is "C_D" equal to each close proximity obstruction. It was solved for using a convergence algorithm.

To validate the coherence of this approach, a series of lab tests were undertaken on 7.6 cm diameter PVC pipes. The test set up consisted of a 2m section comprised of 3 close proximity obstructions with calcite buildup of 7 mm thickness in circumference. This 2m section was placed at 3.65 m from the source. Also, a single obstruction was set at 13 m from the source. Its degree of obstruction ranged from 33%, 50%, 75%, to full blockage of the pipe section. For PVC pipe see chapter 3, the coefficient of attenuation was "$\alpha = 0.016$" and the superposition correction coefficient was "$C_{orr} = 1.33$". Comparing the predicted and actual degree of obstruction at 13 m produced a slope of 0.97 and a correlation of 0.96, Fig. 6.

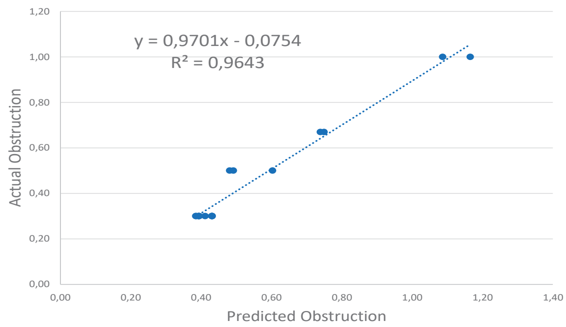

Figure 6 Correlation between predicted and actual obstruction at 13 m, with a section of 3 close proximity obstructions at 3.65 m

6 CAVITIES ALONG DRAINS OF DAMS

In drains of dam, other features than obstructions can induce reflections. They can be categorized in 3 configurations: 1) cavity, 2) open ended, 3) step size increase along the drain.

The pressure wave in air filled drains respects the gas law "$PV = nRT$" which is a constant if the temperature does not change. If the section size does not increase gradually w.r.t. the pressure wavelength, then a sudden pressure drop is created. The positive pressure part of the wave drops below atmospheric. This pressure drop generates in turn a wave that travels back down the drain but with the inverse pressure profile. The acoustic pressure wave is characterized by a change of phase from the incident wave.

Tests were carried out on each configuration with respect to PVC pipe, in order to determine their coefficient of reflections, see Fig. 7.

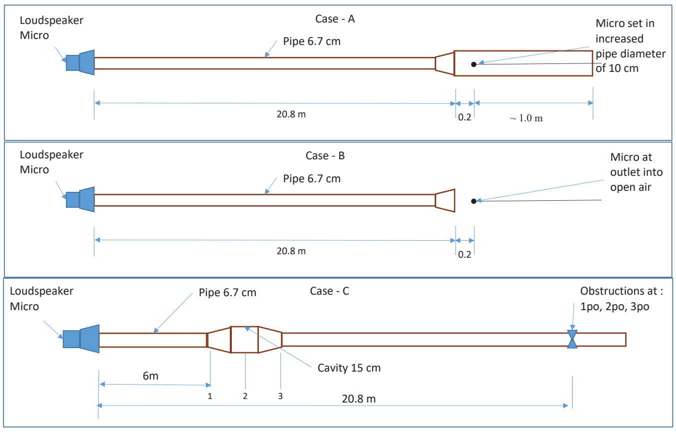

Figure 7 Three configurations of drain section increase: a) step section, b) open ended, c) cavity

The following coefficients of reflections were obtained: in a) there was a step increase in diameter from 7.6 cm to 10 cm, it generated a "$C_D = 0.33$", in b) the pipe lead to an open ended outlet which produced a "$C_D \sim 0.97$", in c) the cavity along the drain with a 15.5 cm diameter section (twice the nominal pipe diameter) over 40 cm generated a "$C_D = 0.82$".

It was interesting to note that as the section increase reached the open-air case, the coefficient of reflection reached unity. The effect of the length of the cavity was not studied.

Also, the transmission power factor had to be established. Therefore, a series of Lab tests were undertaken according to the following set up: a cavity was placed at 6 m from the source and an obstruction at 20m from the source. The obstruction at 20 m was varied in size from a third to complete section obstruction, Fig. 7c.

Through a convergence algorithm, the value of the power factor "*Ctrans*" for the coefficient of transmission through the cavity was established at "*Ctrans = 6.0*", lending a correlation between predicted and actual obstruction at "$R^2 = 0.98$", as shown in Fig. 8.

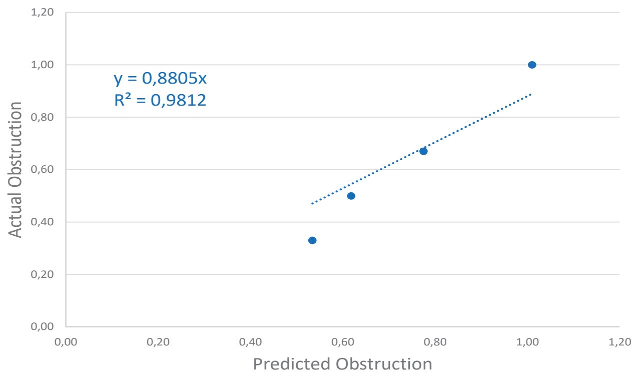

Figure 8 Actual and predicted obstruction given the presence of cavity

7 ACOUSTIC WAVE METHOD CALIBRATED TO DRAINS OF DAMS

7.1 Reality of drains in dams

Field measurements were necessary to calibrate the acoustic wave propagation method in drains of concrete dams. For one, drains in dams are surrounded by concrete. This situation favors "leakage" of the acoustic wave into the concrete, thereby attenuating itself more than in a tube in a Lab resting on sandbags. Other conditions are more related to the drain itself, such as : a) drain walls can present rough surfaces with cracks, stemming from erosion, previous high water pressure cleaning or even drillings, b) obstructions in the form of lobsided deposits of calcite to one side of the drain wall, c) annular calcite accretion along the walls which starts off at a construction joint or crack, d) cavities along a drain arising again from erosion or cleaning, e) outlet of the drain to larger gallery or open-ended to air, see Fig. 9.

7.2 Wave propagation parameters calibrated to dam drain conditions

To establish a coefficient of wave attenuation in actual drains, the approach was to identify from video camera inspections of drains which were completely blocked at their extremities either by water or matter with light obstructions of less than 20% in between. Seven drains presenting these conditions were identified at a given dam. For each drain, two acoustic wave propagation measurements were recorded: at 1100 Hz (λ = 30cm) and at 340 Hz (λ = 1m), each with n = 3 cycles. The two acoustic signals are presented for a given drain showing a noticeable obstruction of 40 to 50% of the drain cross-section at 16 m, in Fig. 10.

It was noticed that the acoustic signal in red at 340 Hz identified more clearly the presence obstructions than the signal in green at 1100 Hz. The acoustic wave at 340 Hz with a wavelength of λ = 1m was less affected by the roughness and leakage into the concrete of the dam. Subsequently, further analyses were focused on the 340 Hz wave pulse. The drains with completely blocked ends permitted to apply a total reflection at the end with coefficient "$C_D = 1.0$" and to apply expression (8). A convergence algorithm on the acoustic measurements on these drains produced a coefficient of attenuation "$\alpha = 0.035$" which was similar to results of the 10 cm diameter FS pipe and a coefficient of superposition “$C_{orr} = 1.33$” similar to the 7.6 cm diameter PVC pipe of same diameter, refer to Table 1.

7.3 Correlation of coefficient of reflection C_D to obstruction size

To correlate the coefficient of reflection, eight other drains were chosen to establish the correlation between the coefficient of reflection “C_D” and the % obstruction of the cross-section area “a/A”. The camera inspection of these drains presented either small obstruction or completely blocked ends. This situation is reflected in the correlation showed in Fig. 11. The correlation obtained was close to unity:

$$a / A = 1.0 \cdot C_D \tag{16}$$

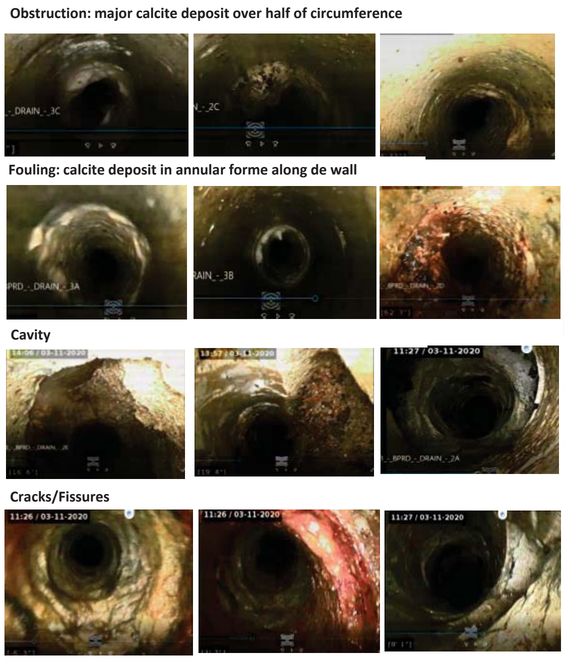

Figure 9 Photos of drain conditions in dams

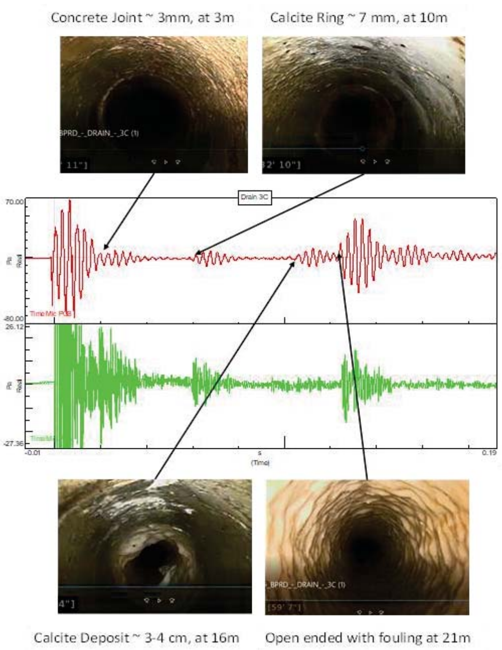

Figure 10 Reflections from obstructions, at 340 Hz in red and at 1100 Hz in green

7.4 Validation of model on drains of dams

The last step was to validate the predictive model on other drains from an older dam which presented more significant obstructions. A total of eight drains were chosen. Some drains out of the eight presented successive obstructions (max of 3) ranging from 30 % to 50%. Some drain outlets went to a collector gallery, while others terminated with full blockage.

Note that the basis of comparison for the predictions came from estimating the video camera screen shot of the obstruction independently. The correlation obtained is presented in Fig. 12. The prediction of obstructions showed a good performance. However, presence of multiple reflections was discarded in the prediction of obstructions.

Figure 11 Degree of obstruction versus coefficient of reflection

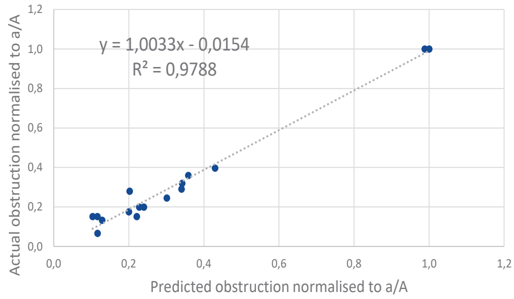

Figure 12 Performance of acoustic method on actual drains

8 CONCLUSIONS

An acoustic wave propagation method was developed to provide a much faster alternative to camera inspection of drains in dams. It was able to predict the position and the degree of obstruction for consecutive obstructions in drains. The difference between annual and lobsided deposit obstruction was not investigated. Nonetheless, the results obtained in actual drains were promising. However, cavities could sometimes be mistaken for obstructions and multiple reflections from defects set within a few meters from the measuring device hindered the evaluation of subsequent obstructions. Henceforth, work is in progress to implement active cancelation of the effect of multiple reflection going back and forth from a cavity or obstruction close to the instrument. Also, work is currently in progress to identify more reliably cavities from obstructions based on phase change of the reflection. Finally, the acoustic signal analysis is being adapted into a software with a rational approach and user-friendly interface that will automate the prediction of obstructions.

REFERENCES

[1] André Taras and K. Saleh, "Non-Destructive Inspection of Corrosion in Rock Bolts using an Ultrasonic Waveguide Approach", Springer, 13th International Conference on Damage Assessment of Structures, 2019, 9–10 July 2019, Porto, Portugal.
[2] Muhammad S, Khan, "An Acoustic Based Approach for Condition Monitoring of Pipes", Journal of the Arkansas Academy of Sciences, Vol 71, Art 33, 2017
[3] Taeho Ju, A. T. Findikoglu, "Monitoring of corrosion effects in pipes with multi-mode acoustic signals", Journal of Applied Acoustics, Elsevir, February 2021
[4] H. N. Mahal, K. Yang, A.K. Nandi, "Detection of Defects Using Spatial Variances of Guided-Wave Modes in Testing of Pipes", Journal of Applied Science, 2018, 8, 2378
[5] Jian Ma, "On-Line Measurements Of Contents Inside Pipes Using Guided Ultrasonic Waves", Doctor of Philosophy, Imperial College London, October 2007
[6] Mustapha Abdullahi, "Detection of Leakage and Blockage in Pipeline Systems", Doctor of Philosophy, Faculty of Sciences & Engineering University of Manchester, July 2019
[7] Zao Feng, K. V Horoshenkov2 and G.Y. Huang, "An Acoustic Method For Condition Classification Of A Water-Filled Underground Siphon", Advances in Mechanical Engineering, 2019, Vol. 11(4) 1–12
[8] Mohd S. A. Yusoff, "Defect Detection in Pipeline Using Acoustic Pulse Reflectometry", Doctor of Philosophy, The University Of Manchester, 2019