Case study: Robotic Underwater Inspection of Concrete Dam Face Prior to Refurbishment

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Abstract –

This case study examines the use of underwater robotic systems to assess cofferdam support faces prior to refurbishment. The inspection process employs a suite of specialized equipment, including a surface preparation robot, geometry measurement tools, and non-destructive testing (NDT) technologies for concrete delamination detection. The integration of these technologies enhances the accuracy and efficiency of structural assessments, ensuring comprehensive data collection and analysis while eliminating health and safety constraints for workers. The findings demonstrate the potential of robotic inspection systems to significantly improve the safety and effectiveness of dam infrastructure maintenance.

Keywords –

Concrete Delamination; Geometry Measurement; NDT; Robot; Underwater; Divers; Dams; Refurbishment

1 Introduction

Hydro-Québec has many hydroelectric generating stations and spillways, some of which were built more than 100 years ago. Our case study focuses on the La Gabelle dam (Figure 1) that celebrated its 100th anniversary in 2024. It has reached a point in its life cycle where some maintenances must be planned. To target the right intervention to restore the life of mechanical equipment and concrete structures, it is important to have quality data that is sufficiently representative of their condition.

In the case of the La Gabelle dam, spillway gates must be refurbished, thus requiring cofferdams to give dry access to workers. Before the cofferdams can be installed, piers' support faces must be inspected to ensure that the cofferdams will be adequately supported and offer appropriate watertightness.

Historically, divers conducted these inspections manually, leading to numerous operational and qualitative challenges. Among these, one can consider the health and safety risks for the divers associated with the dam's conditions (cracks, water infiltrations, etc.) and water currents. Additionally, significant doubt and uncertainty arise regarding the reliability of the measurements due to the following reasons:

- For measuring surface roughness, inspection is done visually using a ruler in turbid and turbulent water.
- For identifying delamination of concrete, inspection is done by manually hitting the concrete surface with a hammer and listening to the resulting sound wave through diving helmet.

To overcome these challenges, Hydro-Québec's Research Institute has developed robotic inspection solutions dedicated to the inspection of hydraulic dams and their features. This paper presents how these robotic solutions were used at La Gabelle to provide civil engineers with reliable measurements while avoiding the health and safety constraints associated with deploying divers in the water.

Figure 1. La Gabelle dam, upstream view of the concrete piers and inspection areas.

2 Surface Preparation

Before conducting laser measurement of geometry and concrete hammering, surface preparation must be conducted. The main purpose of this operation is to remove algae, mussels, and concrete parts weakly clinging on the surface. As shown in Figure 2, this is achieved using two cavitation cleaning domes mounted on a trolley, maneuvered by a multifunctional platform. The platform is shown in Figure 3. Rotating nozzles inside the domes create a strong suction force, ensuring the system remains in contact with the surface. The system can clean rough deposits like barnacles and mussels in up to 17 seconds per square meter, and for algae, it can clean a strip 0.89 meters wide at a speed of 0.5 meters per second.

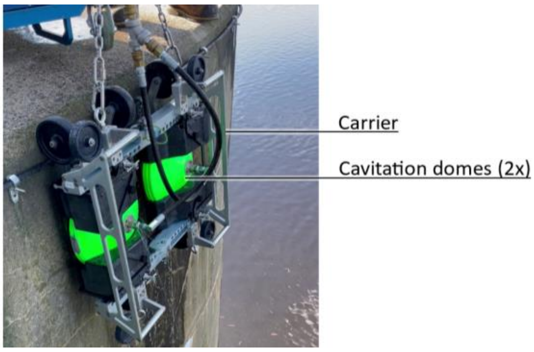

Figure 2. Cavitation cleaning system

The cavitation cleaning process involves water passing through specially shaped nozzles, generating millions of steam bubbles. These bubbles collapse upon hitting the surface, creating tiny pressure waves that remove scale and biofouling such as barnacles, algae, and mussels. This method is highly efficient, easy to integrate onto a carrier, and does not release any residue from the material itself.

Compared to other underwater cleaning technologies, cavitation cleaning is highly effective [1]. Ultrasonic and UV methods have limited capacity and slow efficiency in removing biofouling. Cavitation, bush rotary brushes and water jets achieves over 90% bio-fouling removal. Cavitation cleaning stands out with an efficiency range of 100-1500 m²/h, making it one of the most efficient methods available.

3 Geometry Measurements

Geometry measurements of the contact surfaces are required to evaluate the proper support and sealing of the cofferdams. Flatness and parallelism of the contacts will insure its proper operation. Geometry deviations may result from concrete swelling (e.g. alkali-aggregate reaction) or surface degradation. Erosion and spalling are often found within the tidal zone, where ice thrusts apply.

To assess the geometry, a survey team measured the contact surfaces on the dam, above and below the waterline. Surface digitization technologies are preferred. The resulting 3D point cloud data can be processed to generate vertical cross-sections and heat maps, effectively highlighting any deviation. Offering precision non-contact measurements, a Leica ATS-600 direct scanning laser tracker was used for measurement above the waterline.

Detecting damage on submerged structural elements is often challenging, especially when precision is required. To collect engineering-level three-dimensional measurements underwater, Hydro-Quebec developed the WireScan [2] [3], laser scanner for vertical surfaces that can achieve a ± 1mm accuracy in still water. The system is portable and deployed from the deck, eliminating the need for divers (Figure 3).

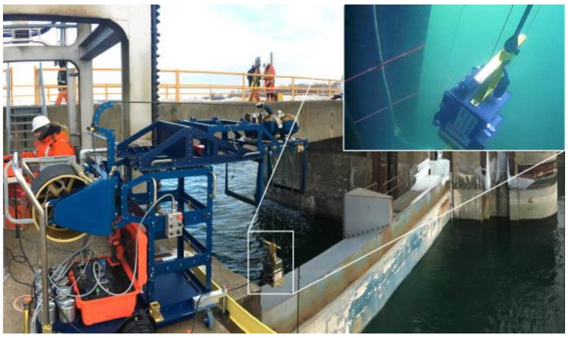

Figure 3. WireScan measurements on a spillway. Underwater scanning (top right). Modular multifunctional platform (left).

WireScan uses two plumb lines as vertical references, maintaining high precision over the range (10 meters at La Gabelle). Supported by its tether, the laser camera slides vertically along wires stretched by weights. Each scan covers approximately 400 mm wide and is positioned in the 3D space with reference spheres measured with the ATS-600.

As depicted in Figure 4**Erreur ! Source du renvoi introuvable.**, results show a large coverage of the top of both piers (with the ATS-600). Below the waterline, the scans focus on the narrow sealing surfaces. Surface damage is visible on the tidal zone just below the waterline.

From the 3D data, it is possible to measure:

- Verticality of the lifting plane
- Flatness defects on sealing surfaces
- Pier-to-pier width at the contact points

The results are shown in Figure 5. The left pier is deviated by +/-15mm around the vertical, while the right pier is deviated up to 60mm to the right. The discontinuity on the left pier corresponds to the horizontal joint shown on the 3D scan.

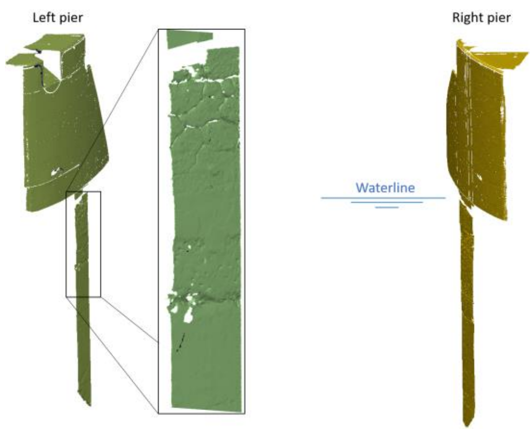

Figure 4. 3D scans of the cofferdam contact surfaces, La Gabelle.

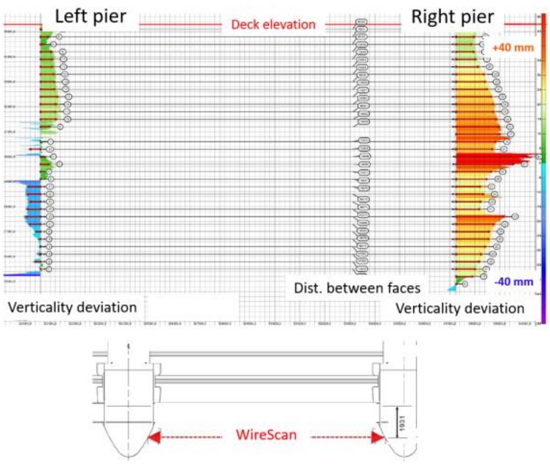

Figure 5. Measurement of the sealing surfaces, elevation view, La Gabelle.

4 Concrete Delamination Detection

To conduct delamination detection, we used an in house developed trolley, see Figure 6, equipped with a motorized hammer to perform impacts and with two hydrophones to acquire the resulting acoustic waves. Striking force consistency is improved compared to traditional methods by mounting the hammer on a shaft axially coupled to a servo motor. As the hammer rotates around the axis, it provides two impact points, 30 cm apart, enhancing inspection coverage. This setup allows precise control of the striking force and additionally offers insights such as the impact angle and the restitution factor. The impact angle can be used to detect surface imperfections, while the restitution force can help improve delamination detection and surface condition. Additional equipment has been mounted on the trolley: a camera and a line laser, allowing for detailed visual inspections and providing valuable information about the concrete's texture, and a vortex suction cup that keeps the trolley firmly attached to the concrete surface it is inspecting. The multifunctional platform mounted on top of the dam, shown in Figure 3, is equipped with a winch, and allows precise positioning of the inspection trolley over the concrete surface.

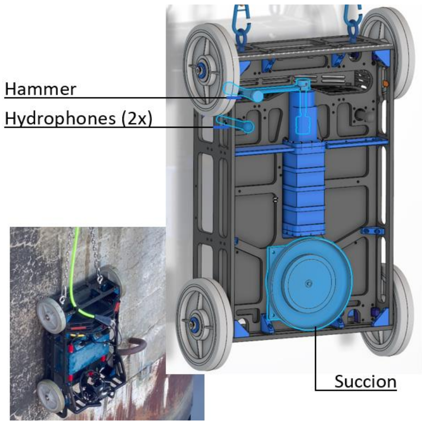

Figure 6. Hammering Trolley.

Hydrophones provide sound pressure resulting (in Pascals) of each impact. From there, we can calculate the sound exposure (see Equation (1)) where *p(t)* is the sound pressure reading from the hydrophone in respect to time *t* in seconds. Using Equation (2) & (3), we obtain the sound exposure level in a dB scale, sometimes referred as SEL_{SS} [4].

$$E = \int_{t_0}^{t_1} p(t)^2 \, dt \tag{1}$$

$$SEL_{SS} = 10 \log_{10} \frac{E}{E_0} \tag{2}$$

$$E_0 = 1 \cdot 10^{-6} \tag{3}$$

Sound exposure levels for each single strike, SEL_{SS}, are computed for each strike's respective duration, where $\Delta t = t_1 - t_0$ is approximately 80ms. In-air measurement would use a different reference level. E_0 and E are given in $Pa^2 \cdot s$.

System has been validated on a concrete block manufactured with known defects. We were able to determine with great accuracy the location of each defect embedded within the block. A software has been developed to map all the readings from an inspection into a heat map, see Figure 7. Our software enables the playback of each impact individually allowing reviewer to determine if a specific section if subject to delamination. Further improvements could be envisioned such as use of Impact-Echo method [5]. However, surface roughness could pose a challenge in producing high-frequency compression wave.

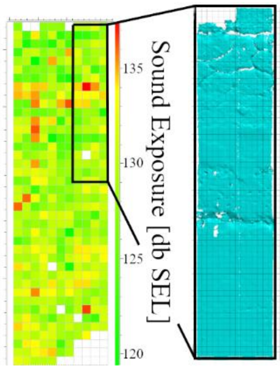

Figure 7. Hammer strike (left) vs WireScan (right).

When compared to measurements obtained from the WireScan, both inspection tools were able to find areas where wears and tears are present. The variation in sound exposure across the inspected surface (+/- 5 %) is not significant enough to correlate with delamination.

5 Conclusion

The adoption of robots in construction projects is anticipated to rise in the coming years, driven by their numerous benefits, including enhanced worker safety, consistency, and precision, among others. In this case study, we demonstrated how robotized inspection solutions developed at Hydro-Québec’s Research Institute were successfully used to obtain surface roughness measurements and to assert presence of concrete delamination on concrete piers at the La Gabelle dam prior to the installation of cofferdams. The benefits expected from the use of robots were confirmed accordingly.

As a starter, all the operational constraints related to health and safety concerns over divers conducting inspections were eliminated. This should be sufficient to justify the robotic inspection project, as the health and safety constraints for divers are so restrictive that, at times, inspection phases of piers are completely abandoned, leading to cofferdam installation work being planned without data on the actual condition of the concrete, which has historically resulted in significant cost overruns.

Additionally, the inspection data that was delivered to the civil engineering team at Hydro-Québec provided unpreceded analysis capabilities. As compared with traditional inspection methods, which only provide maps with approximate areas that require attention, we provided millimeter precision surface roughness measurements, quantitative impact maps that reflect the state of concrete delamination, audio files for playback of all the impacts, and inspection videos. This valuable data will not only enable civil engineers to take more accurate decisions, reducing the risk of cost overruns, but also allow them to compare inspection data of different dams and at different moments of their lifespan, which will inevitably lead to a better understanding of concrete degradation mechanisms.

While the robotic inspection systems demonstrated significant advantages in terms of safety, precision, and data quality, there are still some limitations to consider. One major limitation is the requirement for easy and large access to the top of the structure directly above the inspection area. This can be challenging in certain dam configurations or when overhangs are present, which may obstruct the deployment of the inspection equipment. Additionally, the current system's effectiveness can be hindered by extreme underwater conditions, such as high turbidity or strong currents, which may affect the accuracy of the measurements and the stability of the robotic platforms. Future developments should focus on enhancing the adaptability of the robotic systems to various structural configurations and improving their performance in diverse underwater environments.

6 References

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