UNDERWATER APPLICATIONS OF PREFABRICATED PLUGS USED FOR THE MAINTENANCE AND REPAIRS OF INTAKES AND WATER CONVEYANCE

APPLICATIONS SOUS-MARINES DE BOUCHONS PRÉFABRIQUÉS UTILISÉS POUR L'ENTRETIEN ET LA RÉPARATION DE PRISES D'EAU ET DE CONDUITES

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ABSTRACT

Conventional low-level outlet (LLO) and power intake facilities at dams typically include upstream water conveyance and downstream flow control devices (FCD) such as valves or gates. In many cases, no provisions have been made for isolation upstream of the FCD during the original design and construction of the facility. Minor works or inspections upstream of the FCD are possible with the use of divers or remotely operated vehicles (ROVs), but major works typically require dewatering. Major works may consist of dam safety critical repairs, for example, to address excessive corrosion of steel conduits, degradation of concrete liners, or replacement of the FCDs. Dewatering has been achieved by lowering reservoir levels or installing conventional cofferdams, but often this option is not feasible or cost effective in deeper waters or where watertight conditions cannot be achieved to manage leakage and create a safe working environment or when there are significant financial or other costs to lowering the reservoir. At some facilities, an alternative and innovative solution is to install prefabricated underwater plugs directly upstream of or within the water conveyance. This paper is co-presented by Klohn Crippen Berger (KCB), Empresas Publicas de Medellin (EPM), and ASI Group (ASI). We will review the various plug technologies and some of our recent project applications with various plug sizes, environments, and water depths in Canada and Latin America. This paper will also cover the design processes, construction aspects, key challenges, risk mitigations, safety aspects, and some of the lessons learned.

RÉSUMÉ

Les installations conventionnelles de conduites d'évacuateurs de fond (EF) et de prise d'eau dans les barrages comprennent généralement une portion amont de conduite et des dispositifs de régulation contrôle de débit (DCD) a l'aval tels que des vannes ou des valves. Dans de nombreux cas, aucune disposition n'est prévue pour isoler la partie en amont du DCD. Des travaux mineurs ou inspections en amont des DCD sont possibles avec l'utilisation de plongeurs ou de véhicules télécommandés à distance (VCD), mais les travaux majeurs nécessitent généralement un assèchement (par exemple pour remédier à la corrosion excessive des conduites en acier, à la dégradation des revêtements en béton ou au remplacement des DCD). L'assèchement peut être réalisé avec des batardeaux conventionnels, mais souvent cette option n'est pas réalisable ou rentable à plus grande profondeur ou lorsque des conditions d'étanchéité ne peuvent pas être atteintes pour contenir les fuites d'eau et créer un environnement de travail sécuritaire. Des solution alternatives et innovantes consistent à installer des bouchons préfabriqués.

Dans cet article co-présenté par Klohn Crippen Berger (KCB), Empresas Publicas de Medellin (EPM), et ASI Group (ASI), nous passerons en revue les différentes technologies de bouchons. Nous présenterons aussi les projets suivants récemment réalisés avec différentes tailles de bouchons, d'environnements, et de profondeurs d'eau au Canada et en Amérique Latine. Ce document couvrira également les processus de conception, les aspects de construction, les principaux défis, les mesures d'atténuations des risques, les aspects de sécurité, ainsi que certaines leçons apprises.

1 REPAIRS IN LOW LEVEL OUTLETS - REVIEW OF VARIOUS TECHNOLOGIES

Repairing or maintaining structures and devices in low-level outlets (LLO) and intakes can be challenging when there is no available upstream isolation, or when work needs to be done on or upstream of the upstream isolation device (e.g., maintenance gate, stoplog, or valve). There are a variety of methods that can be used when this type of maintenance or repairs are required; some common methods are discussed in the following paragraphs.

A relatively simple means of dewatering an intake for repairs is to lower the reservoir to a level below the intake. At facilities where lowering the reservoir is possible, this would be one of the preferred methods for completing repairs. However, lowering the reservoir to a level that exposes the intake or LLO can be operationally or functionally challenging at many facilities. As the low-level outlet can be the lowest point where water can be discharged from the reservoir, lowering the reservoir below this point would involve very large pumps or other means of bypassing water flows around the dam.

Using a temporary cofferdam placed at the inlet of a waterway is the conventional means for creating a water barrier to perform repairs and rehabilitations. Cofferdams typically consist of watertight structures such as steel profiles, cut-off walls, earthfill cofferdams, or combinations of water or air-filled barriers with impervious membranes. However, these temporary structures can only be used in relatively shallow conditions as design loads, such as hydrostatic pressures, and foundation conditions can quickly become a challenge. At many facilities the reservoir must be lowered to install the cofferdam. If the facility being isolated is the only means of discharge, a means to bypass flows would be required.

Divers and remotely operated vehicles (ROVs) can be used to execute small repairs underwater but executing work in dry conditions will allow for better quality control, worker safety, and precision in construction – ultimately leading to a more durable result. Working in dry conditions also has an environmental benefit by containing sediment, preventing pollutants from spreading downstream during construction activities, and helping protect local ecosystems by reducing the impact of sedimentation on aquatic life and water quality.

Successful alternatives to cofferdams include placing a temporary plug in the conduit upstream of the first flow control device to avoid dewatering and rewatering and long shut down times. The type of plug technology selected will often depend on the size of the conduit and the depth at which the work needs to be completed. Recent advancements in remotely operated vehicles (ROVs) and global positioning systems have certainly contributed to the development of prefabricated plug technology. Various types of plugs have been used depending on the application and the working environment.

Line freezing, or pipe freezing, is an effective method for isolating a section of piping or a process line. The fundamental principle behind freeze plugs involves cooling the pipe's outer wall to a degree that causes the water to form a plug inside the pipe, adhering to the wall and creating a solid isolation. This technology is typically used in industrial applications for smaller diameter conduits or in small low-level outlets.

For larger diameter conduits and tunnels, the options are more limited and typically involve considerable design efforts, safety considerations, energy, and execution challenges. Ice plugs have been successfully implemented in tunnels using a system of pipes that use liquid nitrogen to freeze the water or a mixture of water and sand inside the intake, but the applications appear to be somewhat limited. The world's first ice plug was demonstrated in a 50 m^2 water tunnel in Norway (Hydro 1995).

Soil freezing techniques have also been successfully implemented in Norway (Hydro 1997). This technology involved freezing a mix of water and sand through an extensive network of cooling pipes filled with liquid nitrogen. Due to the risk of leakage propagation, large amount of energy required for the cooling system to operate, and lack of similar precedents, this technology has not yet been proven in warmer climates. Prefabricated mechanical plugs are considered more reliable to provide a safe downstream working environment for workers, and several successful applications support its efficacy and showcase advancements in repair technologies.

The following section presents four case studies highlighting the implementation and outcomes of various repair methodologies in various environments, providing insights into their effectiveness and applicability.

2 CASE STUDY NO. 1: ST MARY DAM LOW LEVEL OUTLET – AB, CANADA

2.1 Site Layout

St. Mary Dam is located on the St. Mary River in Southern Alberta, approximately 60 km southwest of Lethbridge. The reservoir is part of the Waterton – St. Mary Headworks System, and stores water for the St. Mary River Irrigation District, as well as some domestic municipal and industrial users. The dam was completed in 1951 and is now owned and operated by Alberta Environment and Parks.

St. Mary Dam is a 193 ft (58.8 m) high earth-fill dam. Discharge facilities at the dam include a gated spillway, an LLO, and an irrigation canal. A hydroelectric powerhouse was added downstream of the LLO in 1992. The LLO at the St. Mary Dam is a 20 ft (6.1 m) diameter, concrete lined, circular cross section, 2,120 ft (646 m) long tunnel originally used as the diversion tunnel to divert the river during construction of the dam. At the end of dam construction, a 20 ft (6.1 m) long concrete plug was poured approximately 722 ft (220 m) from the LLO tunnel inlet. A 12 in. (0.3 m) conduit and a 72 in. (1.8 m) conduit were installed though the LLO tunnel plug.

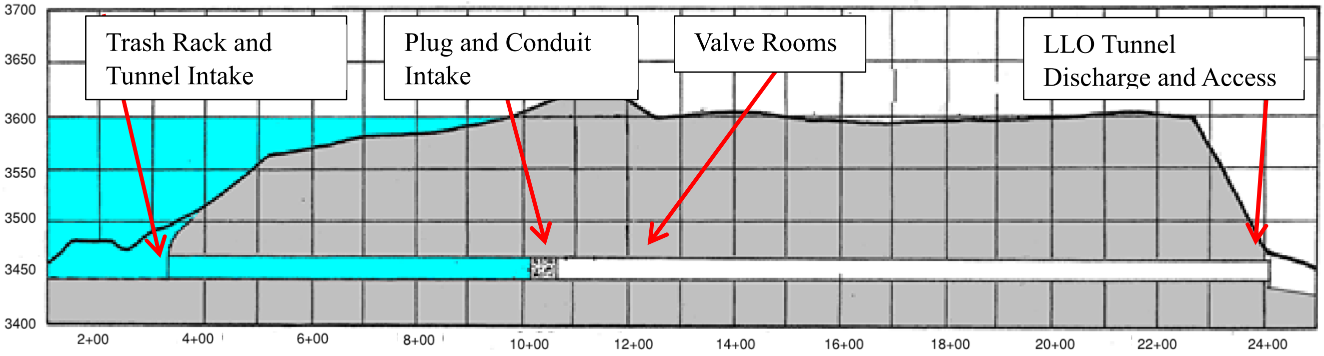

Figure 2-1: Elevation of LLO Tunnel (drawing dimensioned in ft)

Flows through the 72 in. (1.8 m) conduit could be shut off by a 72 in. (1.8 m) guard valve, located immediately downstream of the LLO tunnel plug. A 12 in. (0.3 m) guard valve was installed on the 12 in. (0.3 m) conduit, immediately downstream of the tunnel plug. Downstream of the 72 in. (1.8 m) guard valve, the 72 in. (1.8 m) penstock bifurcates. One penstock branch leads to the powerhouse, and the second branch leads to the hollow jet valve (HJV).

2.2 Problem Definition

Both the original 72 in. (1.8 m) guard valve and the HJV had reached the end of their service life and leaked heavily. Accessing either valve for maintenance was not possible due to this leakage. For dam safety and operational reasons, the valves in the LLO had to be replaced. There were no means to dewater the LLO without draining the reservoir and then pumping inflows into the canal or over the dam. Dewatering the reservoir would have significant financial and operational consequences to the users who rely on the water stored behind the dam. The tunnel upstream of the LLO plug was of unknown geotechnical stability, so installing a plug or barrier at the upstream end of the diversion tunnel was determined to be unfeasible. After an initial round of investigations, a decision was made to proceed with the installation of a plug at the upstream end of both conduits, passing through the LLO plug.

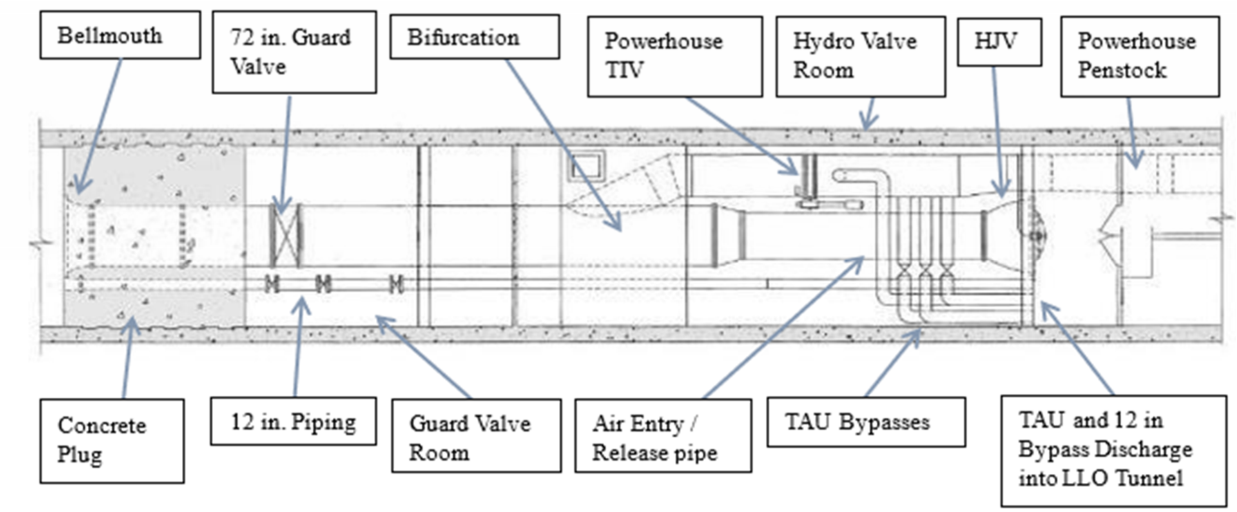

Figure 2-2: Plan of original LLO valves and conduits

2.3 Initial Survey

Before the plug could be designed, the tunnel upstream LLO plug was inspected and scanned using two ROVs. Several attempts were required to remove one trash rack panel at the tunnel entrance to allow the ROV to enter the tunnel. Low visibility in the reservoir and a trash rack partially buried in silt with a design that did not match the as-built drawings complicated this operation. After several attempts and modifications to the equipment, a winch and gantry welded to the barge were used to lift the upper left trash rack panel to allow the ROVs to enter the tunnel. The ROVs scanned the length of the tunnel using sonar, in particular the upstream face of the LLO plug and the conduits. Following the scans, the trash rack section was lowered and riparian flows through the LLO tunnel resumed.

2.4 Preparation for Installation of the Isolation Barriers

The data from the scans was passed to Mechanical Research and Design (MRD). MRD used the scan data to refine the design of two custom isolation barriers, one for the 72 in. (1.8 m) conduit, the second for the 12 in. (0.3 m) conduit. The isolation barriers were fabricated at the MRD facilities and then buoyancy tests and pressure tests were completed for each isolation barrier. The pressure tests were done in full sized mock-ups of each LLO bellmouth at 150% of the design pressure. This gave confidence that when installed, the isolation barriers would have the structural capacity to withstand the reservoir pressure.

The costs and challenges of pumping water over the dam during the initial inspection showed that using pumps to maintain downstream flows for the expected several month shutdown required for the replacement of the valves would be prohibitively expensive. The delay of the installation until 2019 meant that a riparian bypass pipe could be constructed. This pipe diverted water from an irrigation canal to a location immediately downstream of the dam, removing the need for pumps.

Following additional delays due to a change of provincial government, preparation for installation of the isolation barriers resumed in late June 2019. The first step in this process was to remove sufficient trash rack panels to allow the ROVs to enter the tunnel with the isolation barriers. The initial plan was to remove either the upper left and lower left or upper right and lower right trash racks to allow the isolation barriers to be transported into the diversion tunnel. Due to the silt deposits around the tunnel entrance, a significant volume of sediment would have to be dredged from the area in front to the LLO tunnel intake to expose the lower trash rack sections. After reviewing options, a decision was made to cut 1 m off the top of the lower right trash rack section. This would leave the lower portion of the trash rack embedded in the silt while allowing the top trash rack and 1 m of the lower trash rack to be removed, providing sufficient room to pass the isolation barriers.

A hydraulically operated saw was used to cut off the upper portion of the lower right trash rack section. The trash rack saw assembly included a frame which clamped onto a horizontal trash rack C-channel, a linear track that allowed the circular saw to travel across the length of the frame, and a hydraulic umbilical made up of several hydraulic hoses to control the various control functions of the trash rack saw. The circular saw itself had a plunge function that allowed the blade to be retracted while the saw was positioned onto the trash rack and extended while cutting the trash rack. The entire assembly was lowered down on the barge winch and positioned with a ROV. Low visibility made attaching the saw challenging, but eventually the cuts were completed and the trash rack sections removed.

Sediment in the area immediately in front of the concrete plug also had to be dredged to provide the clearance needed for the final installation steps for the isolation barriers. A dredge pump mounted on one of the ROVs was used to moving the sediment 100 ft (30 m) upstream from the concrete plug. Other options were considered that would discharge the sediment downstream through the LLO or upstream into the reservoir, but environmental concerns required that the dredged material remain in the diversion tunnel.

2.5 Installation of the Isolation Barriers

The HJV and the TIV had been closed before the start of work on the trash rack removal. Immediately prior to the installation of the plugs, AEP closed the 72 in. (1.8 m) guard valve to further reduce the leakage flow rate through the LLO tunnel. Due to the age of the valve and the high leakage through the HJV, there were concerns that the valve could not be opened after it had been closed, so closing was left until the first attempt to install the isolation barriers could be made. Once both valves were closed, the leakage downstream of the 72 in (1.8 m) guard valve was measured at approximately 1077.8 gpm (68 L/s).

With the 72 in. guard valve closed, and the leakage rate measurement completed, work began to install the 72 in. (1.8 m) isolation barrier. The plug installation went reasonably smoothly. Two ROVs were used to transport the isolation barrier down the diversion tunnel, one upstream and the other on the downstream side. When the isolation barrier approached the LLO, the downstream ROV disconnected and moved out of the way. Shortly after the downstream ROV disconnected, a power failure on the barge caused the upstream ROV to disconnect from the isolation barrier. The isolation barrier floated free and came to rest on the silt at the bottom of the tunnel. When the power was brought back online, the crews managed to reconnect the ROV to the docking probe on the barrier. That same evening, the isolation barrier was inserted into the 72 in. (1.8 m) conduit. The mechanical seal was activated and the bypass valve through the isolation barrier was closed.

The flow past the isolation barrier, with only the mechanical seal activated, was measured to be between 240 gpm (15 L/s) and 400 gpm (25 L/s). Following these measurements, the inflatable seal was actuated, and a 24-hour waiting period was observed. The leakage flow rate reduced significantly and was measured to be less than 0.03 gpm (2 mL/s), which satisfied the contractual minimum leakage flow rate of 16 gpm (1 L/s). Design criteria for the isolation barrier required that the primary seals not rely on a pressure source, either air or water. Once the mechanical seals had been confirmed to reduce the leakage to an amount that would not be a hazard to downstream workers, inflatable seals could be used to reduce the leakage further. The seals on the isolation barriers functioned extremely well, resulting in very minimal leakage for the duration of the isolation.

Figure 2-3: Installed 72-inch (1.8 m) isolation barrier, from downstream

Several attempts were required to install the 12 in. (0.3 m) isolation barrier. After the first failed attempt to insert the isolation barrier into the 12 in. (0.3 m) conduit, a sonar scan showed that the barrier was not fully seated against the face of the concrete plug. The isolation barrier was extracted and pulled back to surface. The team suspected that the additional tool skid mounted to the ROV for installing the 72 in. (1.8 m) isolation barrier was interfering with the curvature of the concrete tunnel near the 12 in. (0.3 m) conduit.

Subsequent attempts to install the 12 in. (0.3 m) isolation barrier using a smaller, more maneuverable ROV were also unsuccessful. The isolation barrier could not be inserted into the last 6 in. (150 mm) of the conduit. Following removal and inspection of the 12 in. (0.3 m) isolation barrier, evidence of rust tubercles was found on the nose of the barrier. The suspected tubercles appeared to have reduced the inner diameter of the 12 in. (0.3 m) conduit to the extent that there was an interference fit with the 12 in. (0.3 m) isolation barrier. A wire brush attached to a rotary tool was used to remove the tubercles from the inside of the conduit. On the next attempt the isolation barrier was successfully, fully inserted into the 12 in. (0.3 m) conduit. To seat the isolation barrier, the downstream isolation valve was opened, dropping the pressure downstream of the isolation barrier and effectively seating it in place.

The initial leakage flow rate past the mechanical seal was 115 gpm (7.2 L/s). After the inflatable seal was pressurized, the leakage rate was significantly reduced. Following the 24-hour waiting period, 0.16 gpm (10 mL/s) of leakage was measured downstream of the isolation barrier.

The second isolation barrier was installed by the beginning of November 2019. Due to the challenges noted above, the installation took much longer than expected.

2.6 Valve Replacement

Valve replacement work was completed between September 2019 and March 2020 by Simpson Industrial out of Lethbridge. As part of this work, the 72 in. (1.8 m) guard valve and the HJV were replaced, embedded conduits were blasted and coated, penstock sections replaced, a large thrust block installed, and various other piping was replaced. All components for the installation had to be transported 400 m up the diversion tunnel and maneuvered into place.

2.7 Reinstatement of the LLO

To remove the 12 in. (0.3 m) isolation barrier, the bypass valve was opened to balance pressure across the barrier. Once the downstream piping was pressurized, the inflatable seal was disengaged, and the downstream piping was checked for leaks over a 24-hour period. No significant leaks were noted. After several attempts and refinements of the ROV tooling, the isolation barrier was successfully removed.

When the downstream work was complete, the conduit downstream of the 72 in. (1.8 m) isolation barrier was flooded and pressurized by using water from the 12 in. conduit. The bypass valve on the 72 in. (1.8 m) isolation barrier was opened after the penstock was filled. The penstock and connections downstream of the concrete plug were monitored for 24 hours prior to removal of the 72 in. (1.8 m) isolation barrier.

After an assessment showed no leaks, the inflatable seal was disengaged. The following day the mechanical seal was successfully disengaged. A hauling line connected to the barge mounted hydraulic winch was used to remove the isolation barrier from the conduit. When the hauling line was tensioned, the isolation barrier pulled out of the 72 in. (1.8 m) conduit, but the hauling line caught on the frame of the ROV. The isolation barrier had become slightly negatively buoyant and the ROV was unable to prevent the isolation barrier from slowly sinking into the sediment. Lifting bags were attached to the isolation barrier using the second ROV and the small amount of added buoyancy was sufficient to make the assembly neutrally buoyant. The barge mounted winch then pulled the isolation barrier back up the tunnel. The new valves were successfully commissioned in September 2020.

2.8 Safety

During the replacement of the valves, there were no major safety incidents, and the use of divers was avoided. Due to the large depths, the lack of visibility and the long length of the diversion tunnel upstream of the LLO plug, the use of divers would have had significant risks for the deeper dives. The use of ROVs reduced this risk and increased workers' safety.

2.9 Innovation and Project Successes

While there were significant challenges encountered during the replacement of the valves in the St. Mary Dam LLO, the work was completed without any major incidents or major disturbance to the operation of the dam. The installation of underwater isolation barriers using remotely operated underwater vehicles resulted in a fully refurbished LLO with valves and equipment that, with normal maintenance, should be functional for another 50 years. The client, the contractors and the owners of the facility all considered the job successful. Completing this work utilizing any other method would have likely resulted in major interruptions to downstream water supplies or to the irrigation system that supplies much of Southern Alberta.

During the course of the work, winter weather, low water levels, previously unknown equipment layouts, deteriorated piping, a pandemic and a major change in government resulted in many unexpected challenges to what was an already challenging job. A project team – on both the sides of the owner and the contractors

– able to figure out solutions to these challenges was the reason that the project, while somewhat delayed, was successfully completed.

3 CASE STUDY NO. 2: THE PALISADE LOW LEVEL OUTLET PLUGS – BC, CANADA

3.1 Project Background

Palisade Dam, owned and operated by Metro Vancouver, impounds Palisade Lake, one of the alpine storage reservoirs for the drinking water supply to Metropolitan Vancouver. Palisade Dam is located several kilometers north of North Vancouver, British Columbia, Canada. The purpose of this facility is to supplement the water supply for the Capilano Reservoir during the later summer and fall.

The 7.5 m concrete dam and outlet tunnels were completed in the late 1920s. The outlet tunnel is a 600 ft (182 m) long concrete lined tunnel that bifurcates at the downstream end. A cross section of the tunnel is shown in Figure 3-1. Each tunnel ends in a concrete bulkhead.

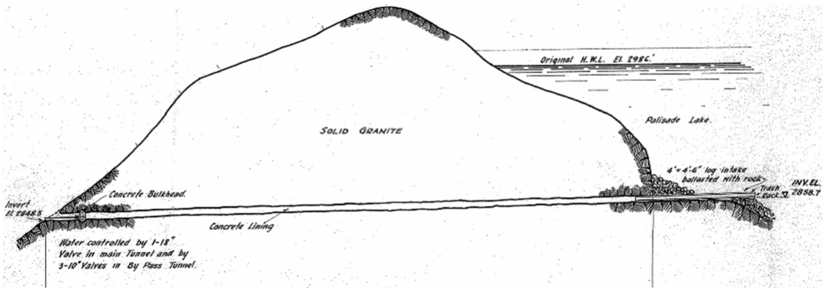

Figure 3-1: Section through the discharge tunnel at Palisade Lake

There are three 12-inch (0.3 m) pipes that pass through the bulkhead in the west outlet and one 18-inch (457 mm) diameter discharge pipe in the east outlet. In the west outlet there is an isolation valve on each pipe approximately 8 feet (2.4 m) downstream of the bulkhead and a fixed cone valve on the end of each pipe. The east outlet has a similar arrangement. The piping arrangement in the west outlet is shown in Figure 3-2.

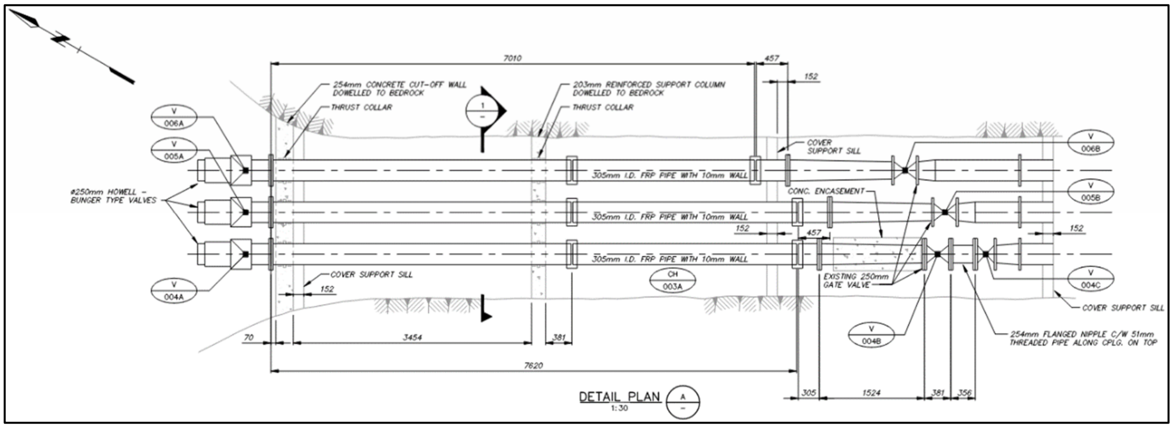

Figure 3-2: Palisade Lake west outlet plan view

3.2 Condition Assessment of Piping

During an assessment of the piping in 2017, piping between the bulkhead and the isolation valves was found to be seriously degraded. Initially, KCB was asked to look at options for replacing the entire outlet facility, but it became apparent that replacement of the facility was a longer-term solution and the condition of the pipes had to be dealt with in the shorter term.

KCB presented several options to Metro Vancouver, these included mechanical or inflatable plugs installed from downstream, pipe freezing techniques, a plug installed from upstream, or dewatering of the lake. Installing a plug from downstream would require working around the existing degraded piping, ice plugs would raise concerns of the stresses on the pipes and dewatering was not an option in the short term.

3.3 Underwater Assessment

In the summer of 2023, ASI Marine used divers and ROVs to inspect the upstream face of the east and west bulkhead. Prior to this assessment, the only information about the inlet to each of the discharge pipes was from the 1920s drawings; these drawings had been found to differ from reality in several other locations on the facility.

Figure 3-3: Pipes in west outlet from upstream

3.4 Plug Design

Based on the information gathered, ASI, in collaboration with Metro Vancouver and KCB, developed a design for plugs that could be inserted into each of these outlets. At the time of writing, these plugs have been designed and will be fabricated and pressure tested in the summer of 2024.

3.5 Innovation and Project Successes

If successful, installation of the plugs will be a simple means of isolating and then replacing the deteriorated piping. In addition, minimizing the proximity of workers to the deteriorated piping will improve workers' safety. Once the deteriorated piping has been replaced, a plan for the long-term rehabilitation of the facility can be developed and implemented.

4 CASE STUDY NO. 3: CHEVES POWER PROJECT – PERU

4.1 Project Background

The Cheves Hydropower Project is located approximately 100 km north-east of Lima, Peru, at an altitude of about 2,000 metres above sea level. It is a run-of-the-river plant that directs water through a 9.5 km headrace tunnel with an elevation change of close to 600 metres where it is discharged through the powerhouse back to the river channel. The tunnel has an inverted horseshoe cross-section with a nominal size of 5 metres. It is mostly rock cut up to a bifurcation that splits it into two steel penstocks.

Inside the powerhouse was a service water line that was leaking through various valves and a flange. This pipe was a nominal 10-inch (25 cm) offtake from one of the steel penstocks and was operating at full pressure. The owner wanted to decommission the pipe to completely remove the leaking fittings. Unfortunately, there was no means of isolating the pipe from the penstock to remove it. The option to de-water the tunnel was not preferable since this would impose excessive stresses on the tunnel as the pressurized ground water was slowly drawn down during the dewatering process. Since it would take several weeks to dewater the tunnel, there would be a considerable loss of revenue to the project as well. The client issued a request for proposal to see if a remotely operated vehicle (ROV) could be used to plug the pipe from inside the penstock, which would allow them to decommission the piping then isolate and close off the connection point with a blind flange.

4.2 Site-Specific Constraints

The distance from the access point near the tunnel entrance to the pipe connection was approximately 9.8 km. The pressure at that point would be equivalent to 600 metres of water, or 60 bar. The pipe was also actively leaking, so approaching the opening could be hazardous; if the plug were installed under flow, it would be drawn in very quickly with the potential for water hammer to initiate pressure waves in a system that was already compromised.

The water at the site is quite turbid with a high silt load, indicating a potential for zero visibility. The lack of any visual feedback would make a challenging project even more difficult. The penstock was tapered at this point. The exact internal diameter of the pipe was not known so any plug needed to accommodate a range of diameters that could seal against a surface that may have pitting and corrosion.

4.3 Design Process

The design team first proposed to isolate the flow in the piping. Since there were no operational valves in that part of the system, a method called hot tapping was proposed to stop the flow in the pipe. This procedure involves installation of a special saddle clamp around the pipe. The clamp incorporates a branch that a valve can be attached to. Specialized tools are then attached to and operated through the valve while the pipe remains at pressure.

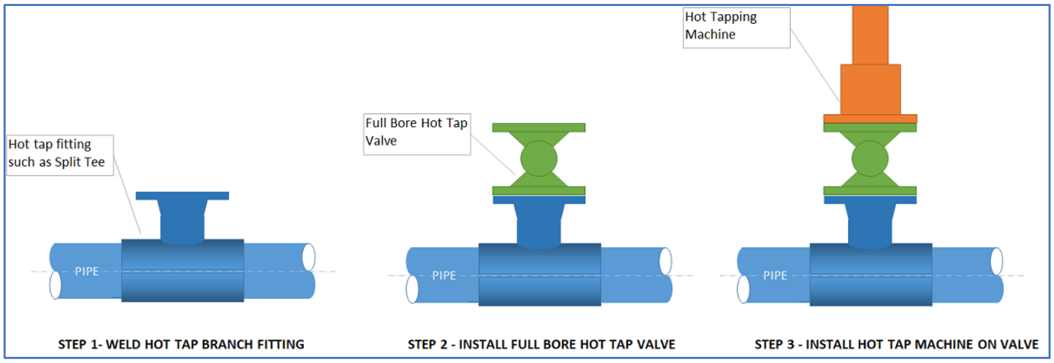

Figure 4-1: Basic steps in hot tapping (https://www.piping-world.com/introduction-to-hot-taps-guidelines-for-design-and-installation)

The hot tapping machine would be used to cut a hole in the side of the pipe. This would provide access for installing an isolation device to stop the flow in the pipe, making it safe to approach from inside the penstock.

A basic approach was used for the design of the plug. Instead of using an expanding plug to seal against the inside of the 10-inch (25 cm) pipe and restrain it in place, a face seal against the inside of the penstock was proposed. Matching the taper and curvature of the penstock at the point of connection was critical for the plug to effectively isolate the piping from the penstock with this type of seal. The penstock was modeled using software, and the geometry of that connection point was copied for the face of the plug. Aluminum alloy 6061-T6 was used for the plug as it has high strength with light weight. Buoyancy would be incorporated into the plug design to offset the weight of the plug and make it neutrally buoyant in the water. The buoyancy would also be used to help align the plug with the centre of the opening.

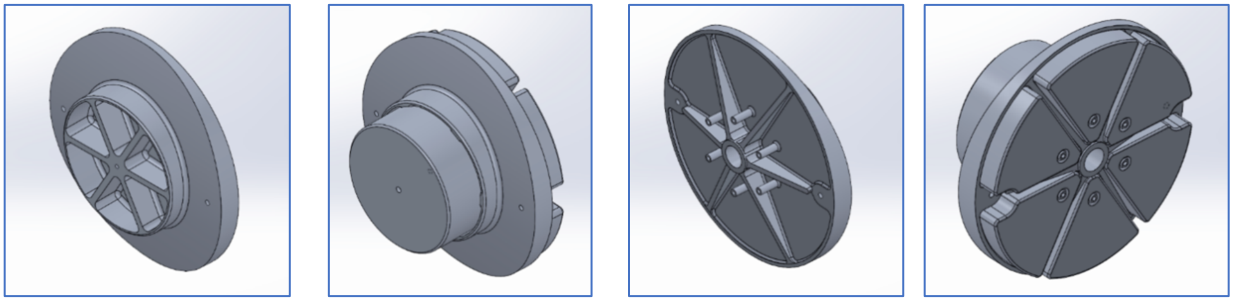

Figure 4-2: CAD model showing back side (left), and pressure side (middle), with and without flotation

4.4 Construction Activities

A specialized team conducted the hot tapping and line isolation works in advance of the ROV crew and installation of the plug. The plant was shut down, and the ROV was deployed for a reconnaissance inspection run to the pipe. (This was the third time that ASI was conducting inspections of this tunnel but the first for any intervention.) Visibility was poor inside the tunnel and once inside the penstock, the silt in the water had slowly worked its way down to the penstock rendering zero visibility inside the penstock. High resolution sonar systems were used for navigation and locating the pipe outlet. Brushes on the ROV were used to clean the sealing area around the outlet and a general inspection of the area was made.

The ROV was recovered to surface and fitted with the plug on a manipulator that was part of the machine. This provided some ability to maneuver the plug to the precise orientation needed to seal the opening. Once the system was checked and verified ready to go, personnel once again flew the vehicle down the headrace tunnel to the penstock.

Figure 4-3: ROV fitted with the plug (left) and downstream view of installed plug (right)

After insertion of the plug, the piping was bled down and removed. The plug provided 100% seal against the face of the penstock, holding back close to 20 tonnes of pressure. A blind flange was then installed to close off the connection point. A small port on the blind flange was used to back-pressure the gap between the plug and flange. This released the plug, allowing the ROV to fly back with the plug, leaving no debris in the penstock that could impact the operation of the turbines. The small port on the flange was closed off and a pipe cap welded over it to ensure full isolation.

4.5 Safety

Stopping the flow of water in the piping prior to installing the plug was a significant step to safely isolate the pipe prior to insertion of the plug. The conservative design of the plug and subsequent testing ensured that it could withstand the pressure to a safe level for the personnel working right next to it. This approach also removed any risk with dewatering the tunnel. It is not uncommon for dewatering a tunnel for inspection to be the cause of a liner collapse.

4.6 Innovation and Project Successes

Using a customized ROV to travel 9.5 km down a tunnel to a depth of close to 600 metres and install a plug in zero visibility is an exceptional undertaking. The plug installation, pipe removal, and recovery of the ROV to the surface was completed in less than 24 hours, an indication that the high level of coordination amongst all personnel led to a successful operation with unique requirements under challenging conditions.

5 CASE STUDY NO. 4: ITUANGO INTAKES REPAIRS AND REHABILITATION, COLOMBIA

5.1 Project Background

The 2400 MW Ituango Hydro project is located on the Cauca River, in the department of Antioquia, approximately 170 kilometers north of the city of Medellín. The facilities are owned and will be operated by Empresas Públicas de Medellín (EPM). The project consists of a 225-m-high earthfill dam and an underground powerhouse on the right bank, adjacent to the dam, and will comprise eight ~300 MW Francis units with a net head of ~ 197.6 m and generating flows of 168.8 m^3/s per unit. The spillway is located adjacent to the right bank and has a maximum discharge capacity of 22,137 m^3/s controlled by four main 21.5 x 16.5 m radial gates and a secondary 3 x 3.9 m radial gate designed to pass a minimum discharge flow. The reservoir extends 75 km upstream and will provide storage capacity for peak generation. The Ituango Hydro project will be the largest hydropower plant in the country and is expected to provide 17% of Colombia's total installed power capacity. The water passages leading to the underground powerhouse include intake structures located on the right bank, immediately upstream of the spillway. They comprise eight 6.6 m diameter inlet tunnels leading to intake gate shafts; the flow is controlled by maintenance and emergency closure gates currently in place. Downstream of the intakes, 135 m high, 6.6 m-diameter steel shafts lead to the generating units in the 240 m long powerhouse cavern.

In April 2018, when the project was nearly completed, the diversion tunnel located on the right bank was plugged, causing the reservoir to rise and threatening a breach of the dam. In a state of emergency, on May 10, the decision was made to open some of the intake gates to divert the flows through some of the intake passages and the incomplete underground openings, to avoid an overtopping of the dam (then at a height of 285 m) and allow for completion of the dam and spillway. The population downstream was evacuated. Thousands of cubic metres per second rushed through several of the intakes, down the 160 m high intake shafts and through the unfinished powerhouse, causing major damage to the civil structures, and destroying most of the electromechanical equipment, leaving the site in a catastrophic state (EPM reported that power of more than 1,400 MW had to be dissipated). The extraordinary energy of the water rushing into the power water passages and caverns powerhouse caused extensive structural damage; estimates indicated the work required to bring the first units into operation would take two years. In 2018, KCB was contracted by EPM to provide several technical reviews for various remediation designs.

5.2 Site-Specific Constraints

The remediation works to be completed at the low-level outlets, upstream of the intake gates included lining of a 28 m long section of concrete liner, and the removal of two concrete plugs immediately downstream of the inlets. Due to the depth of the intakes (located 60 m below the water level) and the impossibility of draining the reservoir, the remediation works needed to be completed underwater or behind temporary plugs. Also, the repairs would need to be completed near an operating spillway and near operating units. Figure 5-1 illustrates the height of the intake structures in relation to the dam and spillway. Due to the extent of the remediation work, executing the repairs underwater was not possible.

Figure 5-1: The water intakes in relation to other structures

5.3 Design Process and Execution

Due to KCB's previous experiences in mechanical plugs, EPM asked KCB to develop technical specifications for this application, participate in a design-build contractor selection process, and participate in the review of the designs. This process was done in collaboration between KCB, EPM, and Integral, the original designer at Ituango. Various concepts of mechanical plugs were proposed and reviewed, and a consortium of international companies led by Netherlands-based DCN was selected to design, construct, and install three mechanical plugs for the three intakes where rehabilitation works needed to be completed. A paper detailing the design process and execution of the work was recently published (Hydro 2023).

The concept of the prefabricated mechanical plugs used at Ituango is illustrated in Figure 5-2. The wedging effect of the plug plate within the concrete-lined bell mouth allowed for a favourable load transfer of the hydrostatic pressures from the rigid plug plate to the surrounding concrete through grout placed in the annulus space. The total dry weight of the plug assembly was close to 80 tonnes and had to be split into pieces for transport by cargo plane from Europe (Figure 5-4). The design was completed based on design criteria developed by EPM and KCB as part of the technical specifications. The design review process included several submissions and design review workshops.

Key aspects of the design included the analysis and evaluation of the mechanism of load transfer to the concrete intake through bearing of the grout layer against the concrete structure, and the evaluation of the performance and capacity of the grout layer between the surface of the concrete intake structure and the plug ring. The governing design hydrostatic pressure was in the order of 830 KN/m^2 under 63 m of head. The design period for Ituango lasted approximately 10 months. The stress transmitted to the concrete through the grout ring was less than 5 MPa. Additional details about the design are presented in a separate publication published by DCN, who was responsible for the design (Hydro 2023).

The watertightness of the mechanical plug system was ensured by a series of upstream and downstream seals. Extensive preparatory works were required, including debris cleaning, removal of trash rack panels assisted by ROV, and 3D surveys of the existing ("as-built") surface of each intake. The model created by the sonar scan was used to develop the final geometry of the plug (the design of the plug component had to account for some waviness and roughness of the concrete surface, which is expected for this type of structure). Sufficient construction allowances resulted in minimal leakage (EPM indicated that the total leakage for one plug was less than 5 L/s).

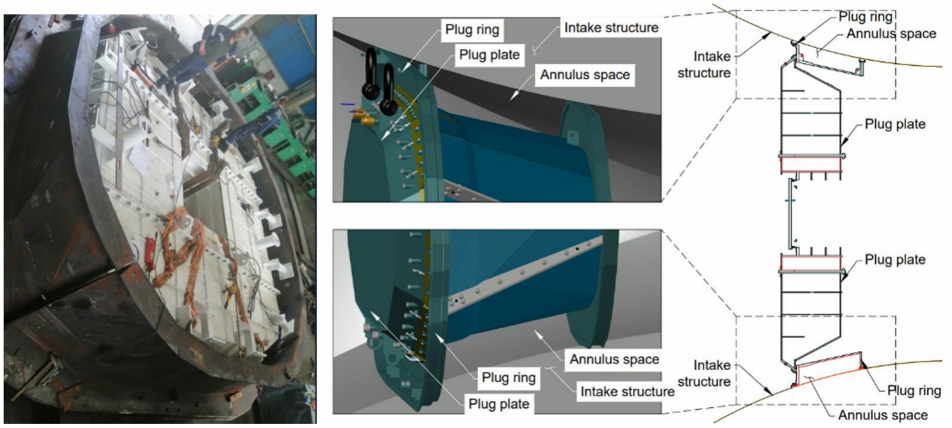

Figure 5-2: Concept of the mechanical plug (Hydro 2023) and mechanical plug at the shop in Croatia

The assembly and installation of the plug on site was done using various barges and cranes. Figure 5-3 outlines the deployment and installation of the plug with controlled buoyancy by foam bodies installed in the plug, a temporary monorail, carriage, and ROV assistance. Figure 5-4 shows photographs taken by EPM during the transport and installation of the plug.

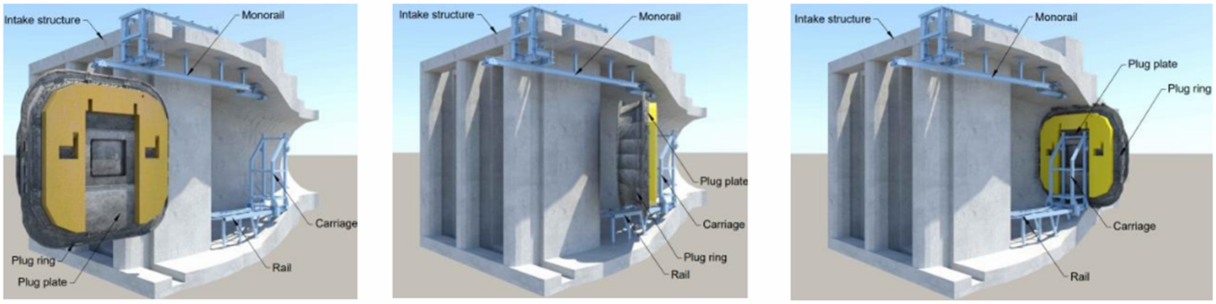

Figure 5-3: Deployment and installation of the plug (Hydro 2023)

Figure 5-4: Transport in cargo plane – Immersion – Demolition of the concrete plugs

5.4 Lessons Learned, Innovation and Project Successes

The installation of mechanical plugs at Ituango can be considered a world's first, considering the size of the water passages, the depth, an environment with zero visibility, proximity to an operating spillway and intakes, and the collaboration of international companies. The unique application of mechanical plugs was a success and allowed for three units to be completed and put in operation.

A few technical lessons learned are presented below (gathered in collaboration between EPM, KCB, and DCN): (1) Design parameters such as hydrostatic levels or water levels must be clearly defined by the client according to the actual standard used on the project with the appropriate safety factors (DIN 19704-1:2014 standard was used for this project). Some design requirements, such as external pressure criteria, are not necessarily covered by design standards and must be included in the design technical specifications. (2) Additional time needs to be allocated for unique and complex designs for non-conventional geometry and environment. (3) Factory, buoyancy, and real scale mock up tests are key to a successful installation. (4) Cultural disparities, collaborating with international consultants and foreign contractors, and the language barrier posed some challenges which had to be overcome. (5) Temporary equipment imports were a challenge and had significant impacts on the schedule.

6 CONCLUSIONS

Underwater works are common in the offshore industry (oil, gas, renewables), and their development in hydro applications is growing. This paper highlights the successful applications of prefabricated mechanical plugs in small and large intakes and low-level outlets. Their applications can allow for significant cost savings, reduced shut down time and loss of production, and, with the help of ROVs and saturation divers, can be executed in zero visibility, providing a known geometry and reasonably smooth concrete or steel surfaces. With aging facilities and increased maintenance, we foresee more applications with the use of mechanical plugs.

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