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CHALLENGES AND ACHIEVEMENTS IN LATIN AMERICA

CONCRETE FACED ROCKFILL DAMS - OPTIMIZING BULB UNIT OPERATION - BEARINGS

Underwater applications of prefabricated plugs for maintenance and repairs works at Cheves and Ituango

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Low-level outlets and intake facilities at dams typically include upstream water conveyance systems and downstream flow control devices (FCD) such as valves or gates. In many cases, no provision was made in the original project design for isolation upstream of the FCD. Minor works or inspections are possible by divers or remotely operated vehicles, but major works typically require dewatering. This can be achieved by lowering reservoir levels or installing cofferdams, but often this is not feasible or cost-effective in deep waters or where watertight conditions cannot be achieved to manage leakage and create a safe working environment. An alternative solution is to install prefabricated underwater plugs directly upstream of, or within, the water conveyance. This papers reviews two recent examples in Latin America.

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 (for example, 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 next.

1. Repairs in low level outlets: A review of the technologies

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 will typically 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 way of creating a water barrier to perform repairs and rehabilitation. Cofferdams typically consist of watertight structures such as steel profiles, cutoff 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 way of bypassing flows will 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, in terms of 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 also 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 [Berggren, A-L., 1995[1]].

Soil freezing techniques have also been successfully implemented in Norway [Knutsson, 1997[2]]. This technology involved freezing a mix of water and sand through an extensive network of cooling pipes filled with liquid nitrogen. Because of the risk of leakage propagation, the large amount of energy required for the cooling system to operate, and a lack of 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.

Two case studies in Latin America highlight the implementation and outcomes of various repair methodologies in different environments, providing insights into their effectiveness and applicability.

2. The Cheves hydro project in Peru

2.1 Project background

The Cheves project is approximately 100 km northeast of Lima, Peru, at about el. 2000. It is a run-of-river plant which directs water through a 9.5 km-long headrace tunnel with an elevation change of almost 600 m, before 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 m. It is mostly rock cut, up to a bifurcation that splits it into two steel penstocks.

Inside the powerhouse was a service water line *(pipe?)* that was leaking through various valves and a flange. This pipe was a nominal 25 cm-diameter offtake from one of the steel penstocks, and was operating at full pressure. The owner wanted to decommission the pipe to remove the leaking fittings completely. Unfortunately, there was no means of isolating the pipe from the penstock to remove it. The option to dewater the tunnel was not preferable, since this would have imposed excessive stresses on the tunnel, when the pressurized groundwater would be slowly drawn down during the dewatering process. Also, since it would take several weeks to dewater the tunnel, there would be a considerable loss of revenue to the project. The client issued a request for a 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.

2.2 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 m of water, or 60 bar. The pipe was also actively leaking, so approaching the opening could be hazardous. If the plug were to be installed under flow, it would be drawn in very quickly with the potential for waterhammer 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 the plug would need to accommodate a range of diameters that could seal against a surface which may have pitting and corrosion.

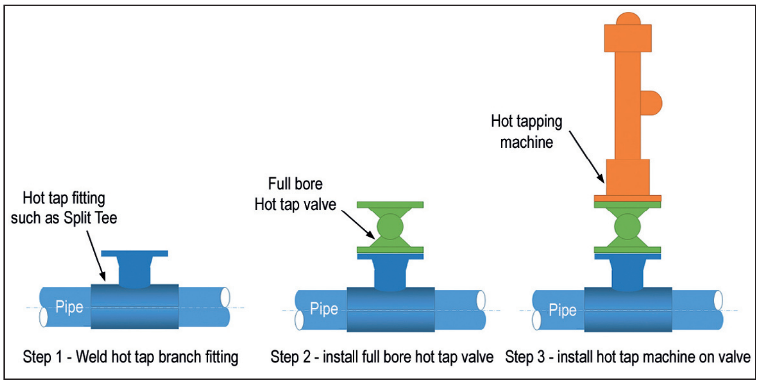


Fig. 1. Basic steps in hot tapping (as used at Cheves).

2.3 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 (see Fig. 1).

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, around the pipe. The clamp incorporates a branch to which a valve can be attached. Specialized tools are then attached to and operated through the valve while the pipe remains at pressure.

A basic approach was used for the design of the plug. Instead of using an expanding plug to seal against the inside of the 25 cm-diameter 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 isolate the piping from the penstock effectively with this type of seal. The penstock was modelled 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 (see Fig. 2.).

2.4 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 had conducted inspections of this tunnel, but the first involving any subsequent intervention.) Visibility was

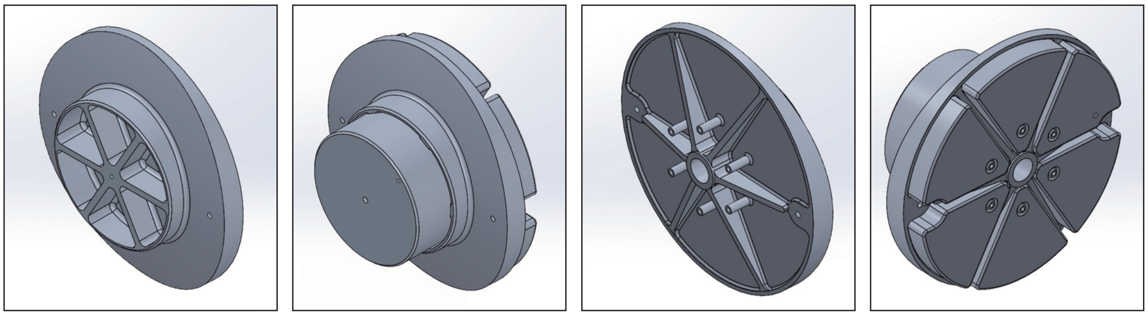


Fig. 2. CAD model showing back side (left), and pressure side (middle), with and without flotation.

The ROV at Cheves, fitted with the plug (left) and downstream view of the installed plug (right).

poor inside the tunnel, and once inside the penstock, the silt in the water had slowly worked its way down to the penstock causing 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 brought to the surface and fitted with the plug on a manipulator that was part of the machine. This provided some possibility to manoeuvre the plug to the precise orientation needed to seal the opening. Once the system had been checked and verified ready to go, personnel once again flew the vehicle down the headrace tunnel to the penstock.

After insertion of the plug, the piping was bled down and removed. The plug provided a 100 per cent 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.

2.5 Safety

Stopping the flow of water in the piping prior to installing the plug was a significant step to isolate the pipe safely 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.

2.6 Innovation and project successes

Using a customized ROV to travel 9.5 km down a tunnel to a depth of close to 600 m 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 among all personnel had led to a successful operation with unique requirements under challenging conditions.

3. Ituango intakes repairs, Colombia

3.1 Project background

The 2400 MW Ituango hydro project is on the Cauca river, in the department of Antioquia, about 170 km north 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 be equipped with eight ~300 MW Francis units with a net head of about 197.6 m and a discharge of 168.8 m^3/s per unit. The spillway is adjacent to the right bank, and will have a maximum discharge capacity of 22 137 m^3/s controlled by four main 21.5 × 16.5 m radial gates and a secondary 3 × 3.9 m radial gate designed to pass the minimum discharge flow. The reservoir extends 75 km upstream, and will provide storage capacity for peak generation. Ituango will be the largest hydro plant in the country and is expected to provide 17 per cent of Colombia's total installed 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.

As described in the article on pp00-00, in April 2018, when the project was nearly complete, the diversion tunnel on the right bank was plugged following its collapse, causing the reservoir to rise and threatening a breach of the dam. On 10 May, 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 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 passed through several of the intakes, down the 160 m-high intake shafts and through the unfinished

Fig. 3. The Ituango water intakes in relation to the other structures.

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 1400 MW had to be dissipated). The extraordinary energy of the water rushing into the power tunnels, vertical shafts, and powerhouse caverns 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 aspects of the remediation designs.

3.2 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. Because of the depth of the intakes (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 had to be done close to an operating spillway and operating units. Fig. 3 shows the height of the intake structures in relation to the dam and spillway. Because of the extent of the remediation work, executing the repairs underwater was not possible.

3.3 Design process and execution

In view of KCB's previous experience with 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 [Calderon, Van der Pennen and Van Oosterhout, 2023[3]], see Fig. 4.

The concept of the prefabricated mechanical plugs used at Ituango is shown in Fig. 5 (right). 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 (see photos on the next page). 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.

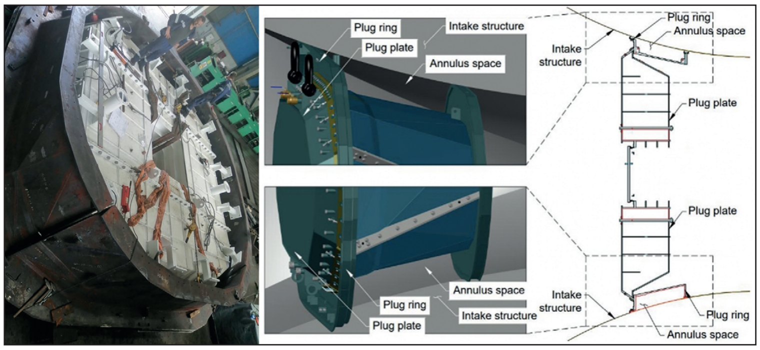


Fig. 4. Picture of the mechanical plug in the workshop, and (right) details of its design concept.

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 of 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 [Calderon, Van der Pennen and Van Oosterhout, 2023[3]].

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 trashrack 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).

The assembly and installation of the plug on site was done using various barges and cranes. Fig. 5 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. Photographs (see next page) were taken by EPM personnel during the transport and installation of the plug.

3.4 Lessons learned, innovation and project successes

The installation of mechanical plugs at Ituango can be considered a world first, considering the size of the

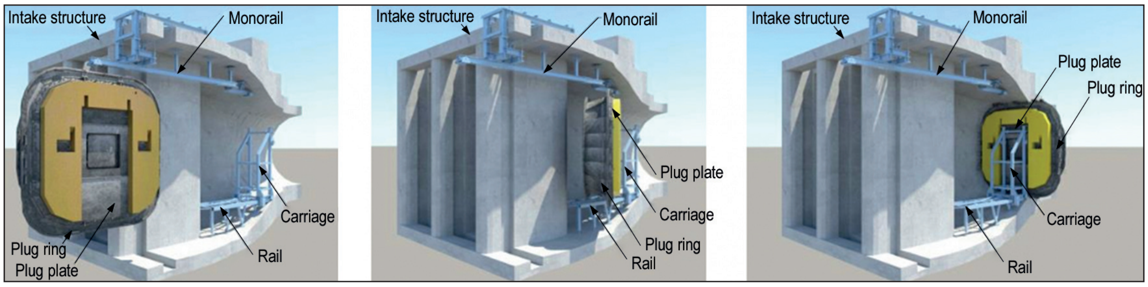
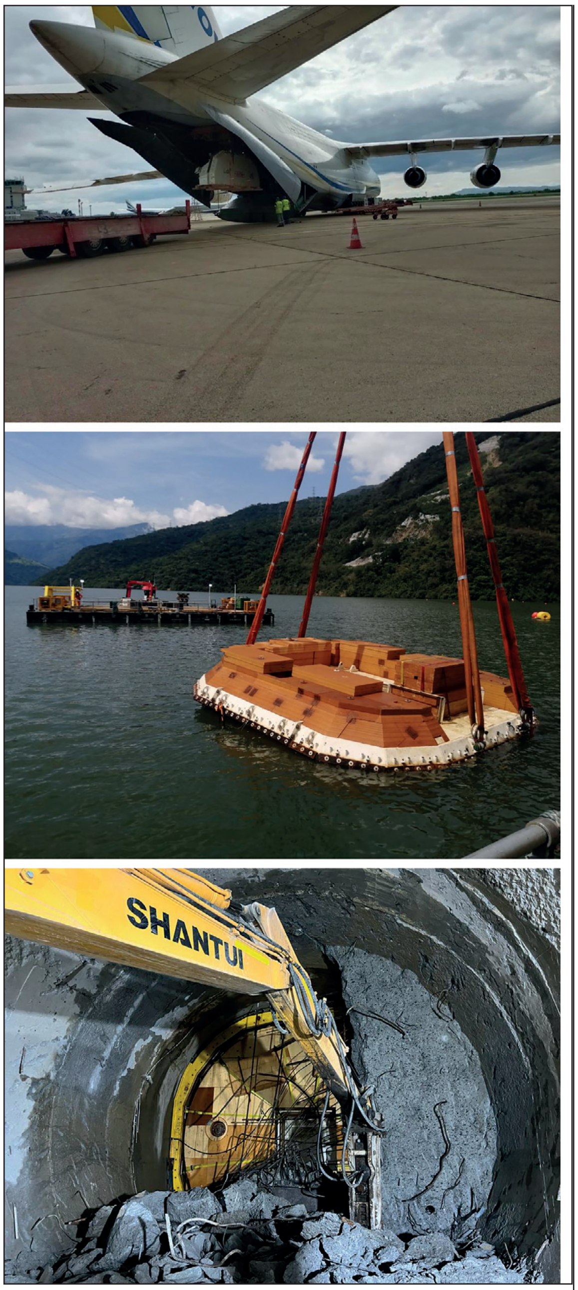


Fig. 5. Deployment and installation of the plug at Ituango.



Views of the transportation of the plug in a cargo plane, its immersion at the site, and demolition of the concrete plugs. (Photos by EPM).

water passages, the depth, an environment with zero visibility, proximity to an operating spillway and intakes, and the collaboration between international companies. The unique application of mechanical plugs was a success and allowed for three units to be completed and put in operation.

Technical lessons learned are presented below (gathered in collaboration with all the companies involved):

- 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.
- Additional time needs to be allocated for unique and complex designs for non-conventional geometry and environment.
- Factory, buoyancy, and real scale mock-up tests are key to a successful installation.
- Cultural disparities, collaborating with international consultants and foreign contractors, and the language barrier posed some challenges that had to be overcome.
- Temporary equipment imports were a challenge and had significant impacts on the schedule.

4. Conclusions

Underwater works are common in the offshore industry (oil, gas, renewables), and their development in hydro applications is increasing. 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, increased safety with the help of ROVs and the limited use of saturation divers, can be executed in zero visibility. With aging facilities and increased maintenance, we foresee more applications with the use of mechanical plugs. ◊

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Robert McLachlan, P. Eng is a Senior Mechanical Engineer, and Manager, Hydro, at KCB, and has more than 25 years of experience in the design, inspection, commissioning and maintenance of large-scale mechanical equipment. He has participated in projects in varying roles, including Project Manager, Lead Design Engineer, Owner's Engineer and Site Engineer. His work at KCB has involved work on various components of dams and hydro plants, including valves, gates, stoplogs, penstocks, piping, HVAC and cranes. His project experience includes dam safety assessments, failure modes analysis reviews, the rehabilitation and decommissioning of hydroelectric facilities, cost estimates and concept development.

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Bob Clarke, P. Eng, has more than 40 years of experience in the marine industry, encompassing commercial diving, atmospheric diving suits (ADS) and remotely operated vehicle (ROV) operations on local and international projects. His responsibilities at ASI have included project reviews, operations planning, execution and supervision of ROV projects, data analysis for the preparation of reports, and proprietary equipment design. As Senior Vice President of Research and Development (Technical Services), he is leading ASI's efforts into new innovations using remotely operated systems to address the needs of ASI's customers.

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Frank Ortiz is a Mechanical Engineer, graduated from the Universidad Nacional de Colombia. He obtained his specialization in Automation from the Universidad Pontificia Bolivariana in 2007 and his MSc in Mechanical Engineering, with a focus on hydroelectric plants, from Universidad de Antioquia in 2018. He has more than 20 years of experience in hydraulic and thermal systems, hydromechanical and electromechanical equipment for water treatment plants and hydropower plants. He has participated in the development of the Ituango project, the rehabilitation of the Playas hydro plant, the modernization of the Ayurá hydro plant and the formulation for the optimization of the hydromechanical equipment for the Guadalupe-Troneras generation chain for EPM. He is currently the Lead Mechanical Engineer for the mechanical plugging and intake rehabilitation at Ituango, using saturation diving, working with EPM in Colombia.

Ricardo Antonio Osorio Tobon has more than 18 years of experience in the structural design of pressurized water conduits and tunnel linings applied to power and water supply infrastructures. Currently, at EPM, he has contributed to the recovery of the Ituango project's intakes by providing technical oversight on underwater works, steel linings, and the development of a discharge flow system, considered as an alternative for intermediate discharge recovery. He holds a Master's degree in Geotechnical Engineering with specialization in Structural Engineering. He is currently working at Medellin at EPM, Colombia.

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