Plugging Ituango's right diversion tunnel: An innovative solution for an unprecedented problem

N. A. Londoño and G. J. Lacouture, Integral SA, Colombia

A major setback, in 2018, for Colombia's largest hydro project was the collapse of a diversion tunnel, causing a hazardous situation for the dam, and a significant challenge for engineers who needed to find a rapid way to access the submerged tunnel and a solution to a problem of unprecedented complexity. Imaginative and courageous concepts, which were rapidly modelled and tested (although their success was impossible to guarantee), along with national and international collaboration, led to an impressive solution. The planning and implementation spanned five years; the permanent plug of the right diversion tunnel was completed in September this year. Together with the commissioning of the first 1200 MW in October 2023 and the completion of underwater works in August this year, the project is back on track.

In April 2018, the construction of Colombia's largest hydro plant, HidroItuango (2400 MW), was only months away from initial commercial operation. In accordance with the schedule, two of its three diversion tunnels had been closed. The Cauca river was being diverted through the third and only remaining diversion tunnel, called the Auxiliary Diversion Tunnel (ADT). On 28 April, this tunnel collapsed, leading to uncontrolled and premature filling of the reservoir, and triggering an unfortunate series of events which represented a major setback for the project. One of the diversion tunnels that had been closed, the Right Diversion Tunnel (RDT), was in the process of being permanently plugged. For that purpose, a cofferdam and a 5 m temporary plug had been built at the tunnel's entrance to protect it from river surges. With this temporary protection, work was under way inside the 14 × 14 m tunnel, in the zone of its permanent plug; the corresponding consolidation grouting of the surrounding rock mass was being carried out. Meanwhile, the permanent plug for the other diversion tunnel, the Left Diversion Tunnel (LDT), had already been completed.

Eventually, the rapid and premature filling of the reservoir led to the failure of the temporary plug at the entrance to the RDT. By that time, the reservoir level had already risen considerably, so the water had a significant amount of energy. Inevitably, three self-limiting and uncontrolled discharges through the RDT, lasting several hours each, ensued. The first two were of the order of 2000 m^3/s, while the third and most destructive was around 6000 m^3/s. In addition, a large landslide fell over the tunnel's entrance. The rubble and debris from the landslide formed a natural plug, which contained the event. Eventually, the RDT was left with a natural rubble plug with an estimated length of 450 m, and the rest of the tunnel's length (750 m) filled with rubble in 90 to 95 per cent of its cross section. Although time and calculations indicated that this natural plug was stable, its stability could not be 100 per cent guaranteed. Access to the RDT was required so that a proper and permanent plug could be constructed, to ensure the safety of the project and the downstream communities. The problem was that access was simply not possible. Both the tunnel entrance and its exit were submerged. The entrance was approximately 200 m below the reservoir level, while the exit was around 20 m below the spillway's stilling basin, with the spillway forced to operate 24/7. However, the principal problem was the amount of seepage flowing through the RDT's natural plug, of around 10 m^3/s, surpassing by at least five- to tenfold the maximum practicable pumping capacity of the contractor.

No precedent for this kind of problem could be found. Therefore, a solution had to be conceived entirely from scratch. To maximize the probability of success, the design was kept as simple as possible, based on elementary physics and behaviours that could be trusted. After various options had been explored, the solution that emerged was to create a system consisting of two temporary plugs, which were to be built remotely, from a nearby tunnel, the Intermediate Discharge Tunnel (IDT). The IDT crossed the RDT 32.5 m above the crown of the RDT, with a favourable trajectory. The purpose of the temporary plugs was to isolate a stretch of the RDT from the stilling basin and reservoir. Seepage from the reservoir should not be stopped since this would mean withstanding the full reservoir pressure of 200 m (35 000 ton). Instead, the function of the upstream temporary plug was to divert the 10 m^3/s of seepage through a by-pass system to the IDT. From there it could be discharged by gravity to the stilling basin. This was accomplished by a system consisting of:

- consolidation of the rubble inside the RDT by injections of resins and cementitious materials, to form the body of both pre-plugs;
- steel micropiles;
- nylon spheres in six sizes;
- six 1 m-diameter down-boring shafts: three for the by-pass and three for sphere insertion; and,
- a filter made of recycled plastic and rubber particles.

1. The problem

The failure of the ADT led to rapid filling of the reservoir. At that time, the main issue was that none of the main works that is, the dam, the spillway, the powerhouse, and the intermediate discharge had been completed. Dam construction had reached el. 384, which was still far from its crest level (el. 435). Since the dam is an earth-core rockfill dam, overtopping was not an option. Therefore, all efforts were directed towards completing the dam and the spillway. Unfortunately, the speed at which the reservoir was rising meant time had to be obtained at great cost: there was no other option but to allow flooding of the powerhouse. This was a drastic and painful situation, but it was the only way overtopping could be avoided. Nonetheless, it was imperative to finish the dam and the spillway as quickly as possible to minimize damage to the power-

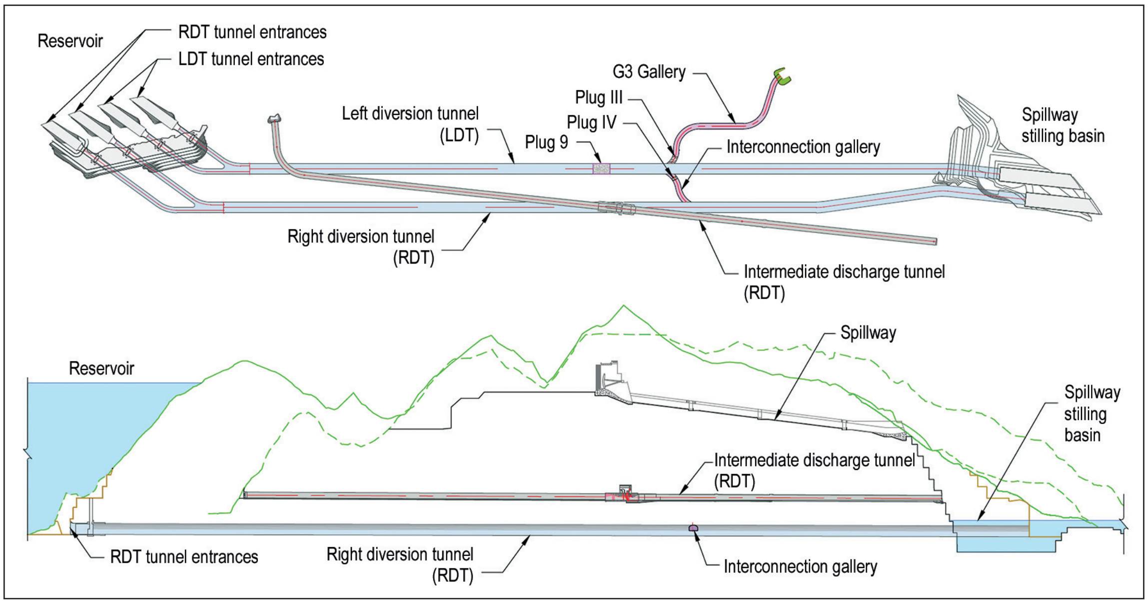


Fig. 1. Plan and profile view of the main elements of the project to solve the problem.

house tunnels and the surrounding rock mass. While work was being carried out 24/7 on the dam, a small but key step towards the plugging of the RDT was achieved. Taking advantage of the fact that the spillway was not yet operating, and as the LDT would be of critical importance to access and plug the RDT, a 4 m plug was built at the exit of the LDT. At least the LDT was safe and protected from the imminent start of operation of the spillway. For a better understanding of this problem, the layout of the main elements of the project are shown in Fig. 1.

Following the events of April and May 2018, the RDT was completely inaccessible. As mentioned, the tunnel's entrance was submerged at a depth of approximately 200 m. Its first 450 m length was filled with a natural plug consisting of the rubble and debris transported by the high energy discharge it had suffered. The remaining 750 m length of the tunnel's 14 m × 14 m cross section was filled to 95 per cent with the same kind of material.

The stilling basin, though not yet operational, was permanently flooded, as a relatively small rock wall or headland that separated the tunnel's exit from the stilling basin had been destroyed by the 6000 m^3/s discharge. This meant that the tunnel's exit was submerged approximately 20 m below water.

Seepage through the RDT's natural plug self-stabilized to around 10 m^3/s. Pumping this water out from the stilling basin was out of the question, since it would have required more than 2 MW of power, and this was not within practicable reach. Moreover, the Ituango river, a tributary of the Cauca river, also contributed to the waters that kept the stilling basin flooded. Diverting seepage flow to the LDT, which would have been easy and would just have required the demolition of Plugs III and IV, would have been useless, since the LDT's exit was at el. 210, meaning that the same 2 MW of power or more would have been needed to pump the water out from the LDT to the Río Cauca's riverbed, which, with the rubble contributions from the RDT's surge, had risen to around el. 230. Dredging the river bed to its original levels would not only have been a difficult and costly task, but also a futile one since the stilling basin's outlet was still at el. 223.

Altogether, there was no way to access the RDT directly. It was evident to all that an indirect strategy had to be conceived. It was then that project engineers realized that the IDT could be the key to plugging not only the RDT, but also the ADT. At the time, the IDT was pressurized, its radial gates had been closed, and although a 12 m plug was located at its entrance, infiltrations had pressurized the tunnel between the plug and the radial gates. Once the strategies for both unconventional tunnel plugging manoeuvres had become sufficiently clear, gradual depressurization and drainage of the IDT was performed.

The IDT and the RDT trajectories are subparallel, intersecting (in plan) right at the location of the IDT's gate zone. These two tunnels are vertically separated by 32.5 m of gneiss rock mass, measured between the IDT floor and RDT crown. The originally planned location of the permanent plug for the RDT was directly below the IDT gate zone, since this location corresponded to the deep impermeable curtain of the dam.

A zone approximately 65 m upstream of the radial gates of the IDT was identified as a good place to access the RDT, providing an acceptable balance between the distance to the RDT with an adequate buffer distance to the point where the permanent plug should be built to preserve alignment with the dam's grout curtain. After dozens of options and variants had been analysed, one scheme began to be considered as the best hope for regaining access to the RDT. The scheme consisted of two 'pre-plugs'; one upstream of the permanent plug, called Preplug 2 (PP2) and another downstream, Preplug 1 (PP1). Both were to be executed remotely from the IDT (and later also from the LDT), so there would be no way of observing directly how works were progressing.

2. Overall strategy

An initial assessment of the condition of the RDT, based on boreholes, measurements from current meters and flow measurements at the stilling basin, indicated that seepage flow was around 10 m^3/s, and that 95 per cent of the tunnel's cross section was filled with rubble. Water was flowing through the upper five per cent of the tunnel's cross section. The main problem was the quantity of seepage, which exceeded the maximum practicable pumping capacity of the contractor.

At an early stage, the contractor reported that one of its subcontractors could drill relatively large diameter shafts from the IDT to the RDT using down-boring (DB) technology. This offered the possibility of diverting the seepage to the IDT. If a controlled obstruction could be created in the RDT, the reservoir's energy would raise the water from one tunnel to the other. Once there, it could easily be conveyed, and discharged by gravity to the stilling basin.

To divert the seepage, a temporary plug started to be conceived (PP2). As mentioned previously, this plug had to be built remotely from the IDT. It needed to fulfil two purposes:

- block the seepage flow in a safe and controlled manner, and force it to rise through the DB shafts from the RDT to the IDT, leaving only minimal residual seepage through the RDT, which could be handled by drainage pumps; and,
- withstand the hydrostatic pressure (of around 50 to 60 ton/m^2, or 12 000 to 14 000 ton) associated with rising the water from one tunnel to the other safely enough, so that people could enter the RDT.

Clearly, doing this remotely from a relatively small tunnel (8 × 8 m) located 32.5 m above the crown of the RDT was not a simple task.

However, assuming successful accomplishment of the RDT to IDT diversion, a second temporary plug (PP1) could be built, also from the IDT, located downstream of the interconnection gallery. This way, a stretch of the RDT could be isolated from both the reservoir and the stilling basin, so that eventually, access could be regained by demolishing Plug IV.

The purpose of the second plug (PP1) would be to work as a cofferdam, isolating the RDT from the stilling basin. With PP2 in place, PP1 could be built in far more favourable conditions than PP2. In fact, a zero or near zero flow condition in the RDT at the location of PP1 could be generated by diverting any residual seepage from the RDT to the LDT through holes drilled in Plug IV fitted with appropriate pipes and valves. Once a zero-flow condition had been obtained, the upper part of PP1 could be built by simply placing anti washout concrete from the IDT above the rock rubble, previously consolidated via grout injections from the IDT. Fig. 2 shows the layout of the temporary plugs, and their main components.

As shown, six 1 m-diameter DB shafts were drilled; three for the bypass system, and three for sphere insertion. The steel lining of the bypass shafts was connected to a system of three 90 cm-diameter horizontal pipes in the IDT. The bypass system was fitted with butterfly valves and annular flow valves. The latter were necessary so that, much later, when the permanent plug was finished, the RDT could be slowly pressurized, at a rate not exceeding 3 m column of water per hour, as dictated by geotechnical engineers.

These preparations were all done in advance, based on the assumption that water could in fact be raised in a totally unprecedented way from one tunnel to the other. If that could be accomplished, the pipes would conduct the water to an open channel further downstream, that would convey it to the IDT's spillway, discharging to the stilling basin. If not, all these costly and time-consuming investments would be useless.

3. Preplug 2

This was the most important and most challenging component of the proposed solution. Its main goal was to by-pass the 10 m^3/s seepage flow from the RDT to the IDT. For this, the flow of water had to be obstructed, but this would lead to pressurization amounting to nearly 15000 tonnes of hydrostatic force. Hence the challenge was both hydraulic and structural. Obstruction of the seepage was to be done via a successive retention system, which would eventually make it easier for water to rise to the IDT though the by-pass system instead of flowing through the RDT. A residual seepage target was set at 500 l/s.

3.1 Successive retention system

The first barrier was to be formed with sixty-three 7 in-diameter steel micro piles (MPs) made from API 5CT casing tubes and buttress thread couplings. They had to fulfil two functions: retain the next element of the obstruction system; and, structurally reinforce PP2 so it could withstand the forces.

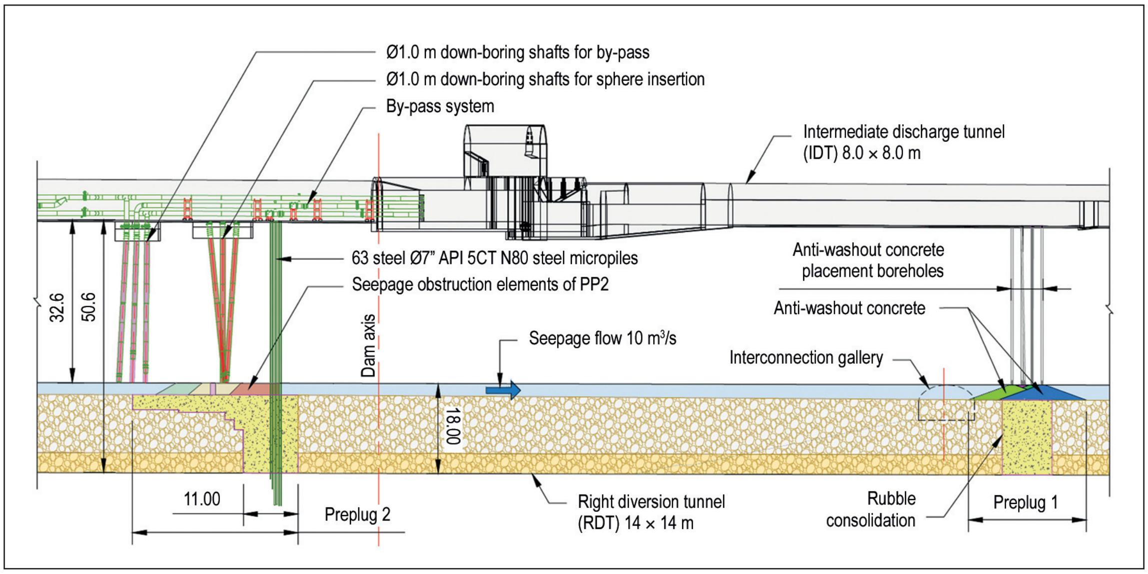


Fig. 2. Layout of temporary plugs PP1 and PP2, that were to be built remotely from the IDT and the bypass system.

The next element consisted of cast nylon spheres of decreasing sizes. For this process, 115 055 spheres with diameters of 70, 47, 35, 17.4, 8.6 and 4.3 cm were to be inserted in that order, through three DB shafts located approximately 12 m upstream of the micro pile screen (see Fig. 2).

The MPs would first retain the 70 cm spheres, which would retain the 47 cm spheres, and so on, through to the smallest ones. The reasons for choosing spheres rather than other types of particles were mainly as follows:

- the hydraulics of sphere transport in fluids is a well known and documented phenomenon; and,
- the fact that spheres do not have any edges, so provided their surface is smooth enough, they will tend not to be retained in unwanted locations offering a favourable capacity of rounding obstacles and reaching the micro pile barrier.

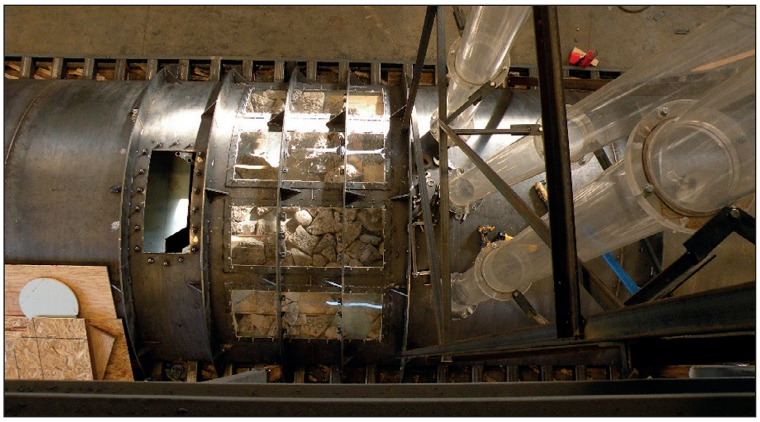
It is important to note that the only 'worker' which could be relied on inside the RDT was the seepage flow itself. The seepage alone had to transport and organize the spheres against the micro piles. As a result, the density of the spheres needed to be adjusted, so as to be very similar to that of the water, but just slightly heavier, so that they could descend through the pressurized DB shafts by their own means. A sphere density of 1.02 ton/m^3 was initially selected.

Evidently, an opening in the system large enough to allow passage of the next component would lead to failure of the whole solution. The criticality of this aspect led to the requirement for the scheme to be tested on a physical scale model before full-scale implementation. Experts from IHE-Delft and the University of Utah (UU) were contacted, and a 1:5 scale model was designed by them and built in the Utah Water Research Laboratory (UWRL), see Fig. 3.

The scale model tests led to many vital observations. First, they showed that the solution could work as planned, provided the amount of water flow would be sufficient. The flow was identified as the single most influential variable. A minimum prototype flow of 4.8 m^3/s would be necessary for the solution to work. Other key findings were:

- An appropriate sphere insertion sequence or protocol was fundamental to achieve the successful arrangement of the spheres. Among the numerous insertion strategies tested at UWRL, one stood out as a 'robust' protocol, proving to be successful under varying conditions. This was very important, bearing in mind that, as opposed to the model, there would not be any acrylic transparent windows in the RDT.

Fig. 3. Overview of the 1:5 scale model at UWRL. Credit: University of Utah, IHE-Delft.



- A sixth size of sphere was recommended (leading to incorporation of the 47 cm-diameter spheres). A second series of tests incorporating this additional size confirmed its benefits.
- Head loss coefficients (k_s) were carefully determined. This was instrumental, since it provided the only reliable means of quantifying and predicting pressure build-up upstream of the spheres.
- A sphere density of 1.004 ton/m^3 for the larger spheres (sizes 70 down to 35 cm) and 1.01 ton/m^3 for the smaller ones (sizes 17.4 cm and below) was deemed optimal for the full-scale application.
- Incorporation of a small percentage of buoyant spheres of the largest reference was found to be effective to fill the upper part of the tunnel's cross section appropriately.

3.2 The filter

The whole purpose of the spheres was to retain a filter. If a filter could somehow be built upstream of the spheres and retained by them, it would block the passage of water and force it to bypass to the IDT offering an optimal, controlled and gradual way of achieving both the bypass and residual seepage goals.

It should be noted that there is a substantial difference between the hydraulic behaviour of the spheres and the filter portions of the system. The pressure gain produced by the spheres is:

$$\Delta P = k_s\ (V^2/2g),$$

while the pressure gain produced by the filter is:

$$\Delta P = (Q \cdot \Delta L)/(A \cdot K) = (V \cdot \Delta L)/K$$

If water is to be pressurized and bypassed, a filter is much more effective, since, once the water starts to bypass, the water velocity through the system (V) will drop. If a low enough permeability can be attained, the filter will provide an excellent means of reducing seepage downstream and raising pressure upstream to generate the desired bypass effect.

What both systems had in common was that they relied on mechanical successive particle-to-particle retention, and both relied exclusively on existing seepage flow in the tunnel as the only 'worker' available to arrange them correctly inside the RDT. All that could be done was to introduce appropriate materials from the IDT (through appropriate boreholes fitted with one-way valves). The rest of the work had to be done by water alone, with no way of seeing how the job was going. Only indirect measurements, such as pressure measurements upstream, could be used to determine if things were going according to plan or not. If things were not to plan, there was very little way of determining exactly what was going wrong 32.5 m below, and how the situation could be remedied.

In recognition of this, it was decided that the feasibility of filter conformation had to be determined and confirmed thoroughly, by laboratory tests, before full scale implementation. Initially, the idea was to 'build' the filter from sand and gravel. However, there were some reservations as to how these particles could be carried and arranged properly by water.

Could the existing water flow transport them and arrange them appropriately inside the RDT? To determine the answer, experts were consulted at the hydraulics laboratory at the National University of Colombia (NUC) in Medellín. After the problem had been analysed with them, it was clear that a model scale test in the strict hydraulic sense would not be feasible, since there were several complex hydraulic phenomena involved with conflicting scaling laws. Fortunately, the main phenomenon that required investigation could be represented reasonably well in a model at the laboratory, and that was the transport capacity of the filter particles. Essentially, it needed to be determined whether the existing water flow and its velocity inside the RDT would be enough to arrange the filter appropriately against the sphere bed. A perspective of the model setup at NUC is shown in Fig. 4.

The first results from the laboratory were not good. Gravel and sand particles were simply too heavy and failed to fill the cross section completely, leaving a large opening at the top through which water could carry on flowing. Thus, a lighter material was required to see if this could remedy the situation. The density of sand and gravel particles was around 2.7 ton/m^3. Rubber came to mind as a possible option, since it has a density of around 1.1 ton/m^3, much closer to that of water. A batch of recycled car tyre particles covering similar granulometry to that of its rocky counterpart was ordered.

Tests with rubber showed some improvement, but unfortunately particles larger than 8 mm came with significant wire content, which not only made them heavy, but also led to entanglement into clusters. Although there was some concern, it still seemed convincing that a lighter material, with a density close to that of water, could overcome these difficulties. One of the sphere manufacturers then made contact, and suggested we should contact a plastic recycling company, which could possibly offer the capacity to manufacture particles to suit our needs.

Required were particles with irregular random shapes of seven sizes from 25 mm to 0.6 mm, mimicking the granulometry of the original sand and gravel filter. It was agreed that they could do it.

They could adapt their recycling facility to produce a mixture of recycled plastic with additions of either talcum or calcium carbonate to fine-tune the density of the product, while irregular particles of all required sizes could be obtained via a shredding and screening process.

Thus, a small order was placed for testing in the laboratory. The results were very encouraging. Finally, a highly effective hydraulic filter, having water flow as the only mechanism to stack the particles correctly against the sphere bed, was being successfully and consistently achieved. In fact, behaviour was such that filter formation worked almost regardless of the insertion strategy. This greatly reinforced confidence in the robustness of the solution at full scale, where there would be only one shot at success. The main conclusions of the tests were the following:

- If particles were inserted in order of descending size, the escape of particles through the sphere bed would either be negligible or non-existent. From an environmental perspective this was important.
- A seven-layer filter with specific layer thicknesses would provide enough transport capacity for the correct arrangement of all layers, even as water velocity was gradually reduced.
- The incorporation of fine rubber particles (from the previous series of tests) to the last layer significantly reduced the overall permeability of the filter, an aspect that was highly desirable.
- Placing the plastic and rubber particles into the RDT could be done by mixing them with water and pumping the mixture with appropriate solid tolerating pumps.
- Having a relatively wide probabilistic distribution of particle densities, including densities slightly lighter than the water and slightly heavier, was highly favourable since it led to simultaneous bidirectional filling of the cross section of the conduit, from top to bottom and bottom to top. This minimized the risks of having holes in the system.

Therefore 105 ton of recycled plastic and recycled rubber particles was ordered, with seven sizes, to be used for the plugging and by-passing of RDT seepage in PP2.

Fig. 4. Filter conformation tests at the hydraulics laboratory of NUC. Left, general perspective; Upper right, failed sand and gravel test; Lower right, successful recycled plastic filter formation. Credit: National University of Colombia.

4. Structural design

The plugging of the flow now seemed to have a fair chance of succeeding. Nevertheless, a structure strong enough to withstand 15 000 tonne of hydrostatic force, and safe enough so that people could enter the RDT, had to be built remotely and blindly from the IDT, with a substantial underground river running in between.

The concept was simple: since the RDT was filled 95 per cent with rock rubble, the idea was to consolidate the rubble via injections of various materials: antiwashout grout, ordinary cement grout and polyurea silicate resin. But this was easier said than done. It proved to be by far the hardest of all the jobs to be carried out for plugging the RDT. The main difficulty lay in the heterogenous, unconfined nature of the material that needed consolidation, with a free surface that no one could see, exposed to 10 m^3/s of running water. Without confinement, injection materials could easily migrate to the free part of the tunnel, either through pores in the rubble or through the annular space of the boreholes if these could not be properly sealed.

However, agglomerating the rubble was crucial; without a sufficiently sound and stiff consolidated rubble block, the micro piles would not work as required, as they would work in flexure rather than shear. Their 18 cm-diameter cross section compared with the 18 m height of the RDT (14 m of original tunnel height plus 4 m average scour), clearly meant they were not suited for flexure. The only way they could act properly was to be embedded in a stiff rubble block, which would force them to work in shear. Even then, all structural models including those of Integral and of the advising consultant (Lombardi SA, Switzerland) predicted that the micro piles would incur some degree of plastic behaviour. The important thing was to limit the plasticity, allowing relatively small plastic strains.

The injections were not only necessary for structural purposes, they were also vital to reach the seepage goal, and avoid water from passing beneath the filter.

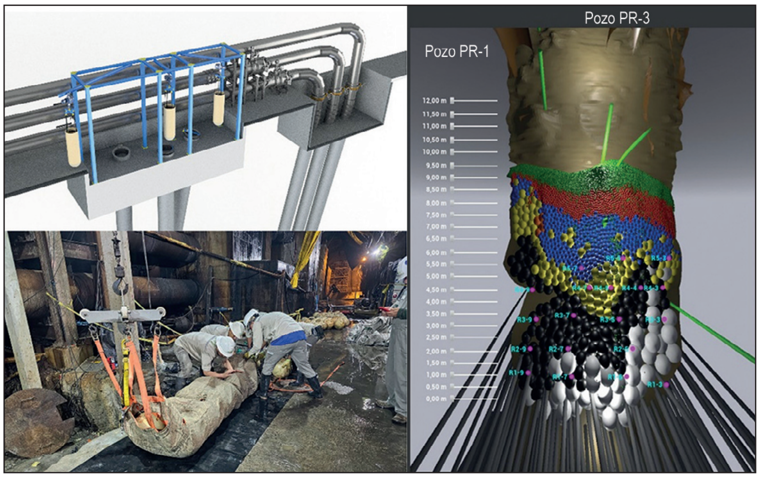


Fig. 5. Sphere insertion. Top left, System design for the insertion process; Bottom left, loading of the spheres into the special polyester bags. Right, Sphere arrangement simulation. Source: Integral SA.

In view of these needs, much time and effort were put into the injections. The effectiveness of the injections was determined based on inspection of borehole cores, permeability tests and finally through ASTM D4719 pressure meter tests. These confirmed that a satisfactory average value of elastic modulus had been attained. However, since real structural behaviour of PP2 remained highly uncertain, three of the micro piles were fitted with permanent shape array instruments (Measurand SAAVs). These high sensitivity instruments would reveal exactly how the micro piles were deforming at any given time under load. This provided a quantitative means of establishing whether the structure was safe enough for people to enter the RDT.

5. Implementation

In August 2022, the first sphere insertion manoeuvres were carried out. The spheres were lowered in batches through the DB shafts and released less than 1 m above the water line, using specially designed polyester bags equipped with a quick release mechanism, such as are used for water release from helicopters. This system was also tested and fine-tuned in a mock-up arrangement outside the RDT prior to the actual insertion. A drawing and a picture of the sphere insertion device is shown in Fig. 5.

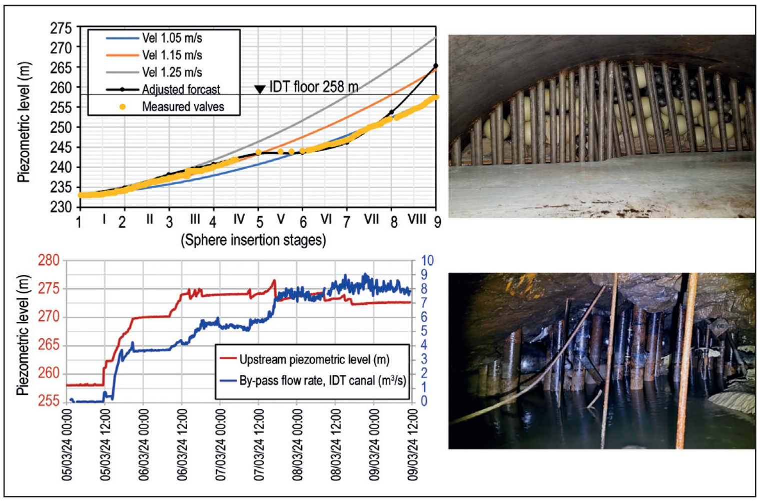


Fig. 6. Pressurization of the RDT. Top left, pressurization resulting from the sphere insertion. Initial predictions are shown by coloured lines for different mean water velocities in the RDT. Finer prediction is shown by the black dotted line. Real behaviour is indicated by red dots. Bottom left: pressurization resulting from filter conformation. The IDT floor is at el. 258. Upper photo: sphere stacking against the micro pile screen at UWRL's model in 2019. Lower photo: spheres stacked against the actual micro piles inside the RDT in April 2024. Sources: UWRL and Integral SA.

During the sphere insertion, determining whether the manoeuvre was progressing as required was done by monitoring several indirect variables, including monitoring the system's response in terms of pressures changes upstream, through several piezometers, depth measurements performed by simply lowering a steel rod through existing boreholes where sphere stacking was expected, and flow velocity measurements inside the RDT, using a micro current meter adapted to the tip of a torpedo and designed to fit into HQ size boreholes.

Real pressurization obtained by the sphere insertion was compared with predicted pressurization according to the head loss coefficients that had been determined at UWRL, as shown in Fig. 6, top left. Meanwhile the pressurization caused by the filter, which led to the successful bypass activation is shown in Fig. 6, bottom left.

6. Results and conclusions

After more than five years of hard work, access to the RDT was regained via the remote and blind construction of two temporary plugs, of which some of the key details have been provided in this article. Neither the problem nor the solution had any known precedents, which meant success was far from guaranteed. The challenge was huge and so were the stakes, for this was the only remaining major hurdle for Colombia's largest hydro scheme to get fully back on track after the unfortunate events of 2018, which destroyed a major portion of what had been built.

The solution was a total success, surpassing all expectations and even the most optimistic forecasts, both in terms of residual seepage and structural behaviour. Seepage through the PP2 was eventually reduced to less than below 100 l/s, at least five times less than expected. The consolidation of the rubble was thorough and effective, and the micro piles remained elastic during the whole time, even during and after excavations had been completed downstream of PP2 for construction of the permanent plug, which was successfully completed on 18 September 2024. The bypass is still operational and at the time of writing was planned to be closed soon. HidroItuango is now producing 1200 MW of power for the national grid and will provide 2400 MW in total when the project is complete. ◊

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N.A. Londoño, a civil engineer, graduated from the Universidad Nacional de Colombia in 1999. He holds a PhD from Carleton University, Ottawa, Canada, awarded in 2006. He joined Integral SA (Medellín, Colombia) in 2007 where he has worked on the design and construction of a wide variety of hydroelectric projects and components including intake structures, bottom and intermediate outlets, powerhouses, sluice and radial gate support structures and small run-of-river projects. He has also coordinated the structural design of other projects, ranging from industrial facilities to transportation infrastructure.

G. J. Lacouture, also a civil engineer, graduated from the Universidad Escuela de Ingeniería de Antioquia (UEIA), Colombia, in 1990; in 1995 he obtained a Master's degree in Irrigation Engineering from the Centro de Estudios e Experimentación de Obras Públicas (CEDEX) in Madrid, Spain. He has worked as a Lecturer at UEIA and Universidad EAFIT in Medellín. He joined Integral SA in 1989, where he is currently the Technical Leader in Water Resources. His fields of expertise include planning, monitoring and execution of hydrology, hydraulics and sediment studies and designs related to dams and numerous types of water related works.

Integral SA, Cra. 46 N° 52-36, 050012 Medellín, Colombia.

N.A. Londoño

G.J. Lacouture