# Independent Advisory Panel to IDB Invest
# IAP Report N°4, June 2020
# Ituango Hydropower Project
# Colombia


**Federico Ciampitti**
*Hydraulic, Mechanical & Electric Equipment*

Via L Tolstoi 72, 20146 Milan Italy
Tel. +39 335 1007517
Federico.ciampitti@gamail.com

**Pavlos Marinos**
*Engineering Geology and Geotechnical*

23A, Penetoliou str. 11741, Athens, Greece
Tel. +30 694 4301993
marinos@central.ntua.gr

**Alessandro Palmieri**
Dam Engineering and Safety (Chair)

Via Massimi 25, 00136 Rome, Italy
Tel. + 39 063 5400737
Arp.palmieri@gmail.com

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# ACRONYSMS

| | |
|---|---|
| ADT | Auxiliary Diversion Tunnel (GAD or SAD in Spanish) |
| BID | Banco Interamericano de Desarrollo |
| CAP | Reservoir capacity |
| EPM | Empresas Públicas de Medellín |
| FEM | Finite Element Analysis |
| IAP | Independent Advisory Panel to IDB Invest |
| IDG | Intermediate Discharge Gallery (DI in Spanish) |
| MAF | Mean annual flow |
| MAS | Mean annual sediment yield |
| MLO | Middle Level Outlet |
| ANLA | National Authority of Environmental Licenses (ANLA in Spanish) |
| PH | Powerhouse |
| PF | Probability of Failure |
| PFMA | Potential Failure Mode Analysis |
| TD2 | Diversion Tunnel 2 (right) |
| EBIA | EPMs Board of Independent Advisors |
| masl | Meters above sea level |
| SNL | Speed-No Load |
| PFMA | Potential Failure Mode Analysis |

## EXECUTIVE SUMMARY AND RECOMMENDATIONS

Despite the unprecedent events that impacted the Project, the implemented measures allow to express a satisfactory assessment on the safety of both surface and underground works.

Plugging the DT2 has suffered delays, and it remains the most urgent activity. Its planning is fully satisfactory and the technological measures that are being adopted are appropriate. Satisfactory contingency planning is also in place to overcome unforeseen developments. Once plugging is successfully completed, the safety conditions for the population downstream will return to normal.

A PFMA workshop was held to address the subject of effective reservoir control during operation. Two key measures were identified for that purpose:

- Operate the turbines at elevations below 390 masl, and
- Adding a Mid-Level Outlet (MLO).

The former measure appears technically feasible; supplier's opinion is essential, including feedback on guarantees efficiencies.

The decision to build an MLO should be Risk-Informed, i.e. the PFMA workshop should be repeated, with more detailed probability estimates, and the risk level compared to that associated with the construction of an MLO.

The behaviour of the dam is satisfactory. The positive effect of the diaphragm wall in the upper part of the dam is evident**.** Given the observed performance, that area should be considered "definitive filling".

Treatment works on the right bank slopes above the intake works are proceeding satisfactorily. The IAP renews its recommendation to extend the necessary treatments to the slopes further upstream, where mass movements took place in 2018.

Performance of the spillway's plunge pool is satisfactory to date. When, with turbine operation, access is possible, a thorough assessment will have to be done and the opportunity to pre-excavate part of the pool evaluated.

Despite the extremely high and uncontrolled energy dissipation that occurred underground, for a long time, overall rock-mass behaviour is satisfactory. Remarkably, no progressive failure due to stress re-distribution has been observed.

Pressure conduits and underground openings in the North side of the Power Complex are in advanced phase of rehabilitation and the remaining repair works are substantially defined. The IAP recommends considering the adoption of drainage holes through the planned backfill of Almenara 1.

In the South side, the rock mass appears of lower quality. The IAP recommends preparing a zoned classification of the rock mass, giving due consideration to the reliability of the cores. The design of rehabilitation works should be based on actual rock mass defects (open joints, shear zones, loose rock, cavities etc.) and associated potential mechanisms of failure.

In the South side, the underground complex features a maze of temporary and permanent galleries, some of which may induce hydraulic gradients towards permanent openings. A Plugging Plan, which carefully sequences plugging, lining, and grouting works, is necessary to manage risks of hydraulic fracturing, drainage plugging, damage to permanent linings, etc.

Several options are under study to enable the IDG for releasing ecological flow. The IAP supports option 5, featuring an additional shaft and tunnel. Such option permits to activate the waterway without opening the intake at el. 260 under water. The IAP points out that, during the life of the project, it could become valuable to flush sediments below the intakes and prolong the life of the project. To that effect, the need to open the IDG intake at el. 260 may be reconsidered, during the life of the Project. Planning should be based on bathymetric surveys. In advance of its next visit, the IAP would like to review the surveys carried out to date.

The decision of total replacement of Unit 3 and Unit 4, including first and second phase concrete and embedded parts basically completed the assessment of electromechanical equipment and allowed the placement of all orders necessary to reconstitute the entire electromechanical supply of Ituango.

EPM's March 30, 2020 schedule features the following milestones:

| *Unit* | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| *Commencement of operation* | December 2021 | April 2022 | July 2022 | October 2022 |

With the marginal reserve on the complex activities associated with the completion of the intakes to units 2, 3 and 4, the IAP considers the schedule attainable.

Reliability of cost estimates is good for the E&M equipment because most of the additional costs are expected to be sustained by the insurance companies.

More investigations and tests are necessary to adequately define the civil works required for commissioning units 5 to 8. The IAP considers premature to assess the relative cost implications, until investigations and design have reached a sufficient level of reliability.

The IAP considers reasonable allocating a contingency of 50 M$ to face unforeseen requirements in the civil works necessary for commissioning units 1 to 4.

# 1 CURRENT PROJECT SITUATION

## 1.1 General

The Ituango Hydroelectric Project is under construction at the northwest of Colombia since 2009. The Independent Advisory Panel (IAP) was formed in 2018 to advise IDB Invest on technical matters of primary relevance to safety and sustainability of the Project. The IAP visited Ituango three times, in August 2018, March 2019, and September 2019 and issued respective Reports.
The fourth mission, of May 2020 had to be organised virtually due to the concomitant C19 pandemic. All three IAP members attended the mission. Despites the difficulties, thanks to an excellent organisation by EPM, and facilitation by IDB, the virtual mission allowed the IAP to appreciate the progress made and get an update on the main technical issues of the Project.
The mission was composed by three video conferences, on May 19th, 20th, and 21st. The first two days were dedicated to presentations and discussions. On the last day, the IAP gave a brief of their preliminary observations, which are elaborated and presented in this report, followed by the PFMA workshop. The latter was delivered by the IAP to assist EPM making a risk-informed decision on the subject of reservoir control during Project operation.
The sessions of May 19th and 20th were attended by EPM and its Consultants.
Members of the EPMs Board of Independent Advisors, and of Poyry also attended the IAP brief and the PFMA workshop of May 21st; annex C to the present report contains the full list of participants.
The IAP wishes to acknowledge the highly professional contribution of all stakeholders to the discussions and exchange of views on the complex technical subjects pertaining to Ituango HPP.

## 1.2 Comparison with October 2019

During the IAP's May 2020 virtual mission, the situation of the Project has considerably evolved in comparison to September 2019:

- Performance of the dam is in line with design expectations and correspondence between predicted and as-measured performance is excellent.
- The spillway is operating full time, which is beyond the design assumptions, and will continue so until turbine operation will be established. Monitoring of the plunge pool slopes do not show any sign of unacceptable distress.
- Most of the underground areas, which were affected by uncontrolled river throughflow, have been inspected and needed repair works defined. The large cavity between pressure shafts 1 and 2 has been successfully backfilled.
- Safety and security conditions have been re-established in most of the areas and progressing satisfactorily elsewhere.
- Of the remaining works, required to commission units 1 to 4, stabilization of the connection between PH Cavern and Almenara 1 is the more challenging; the experience acquired on the successful filling of shafts 1-2 cavity will help the conduction of the works.
- Design and methodology for plugging RDT and GAD are advanced and activities by specialized contractors are ongoing, though some of them are demonstrating to be more challenging than expected.
- The contract for the new penstocks was signed and the contractor is proceeding with material supply and mobilization.

- After the negative assessment of the embedded parts of unit 3 and 4, the hypothesis of a partition of each shaft chamber in two halves was abandoned and the sequence of erection and commissioning of the units defined.
- Procurement through several packages of the damaged electromechanical equipment is substantially completed.
- The design change, placing the intake of the IDG at higher elevation using a vertical shaft connected to power intakes, was adopted; detailed design is underway.

### 1.3 Options for Project's Completion

The following table shows the progression of IAP assessment of the "Options for Project Completion" which were put forward since the IAP's involvement in the Project.

| Options | August 2018 assessment | March 2019 assessment | October 2019 assessment | May 2020 assessment |
|---|---|---|---|---|
| Full Rehabilitation | Preferable option; final confirmation after assessment of damages in the powerhouse complex | Confirmed preferable option | Substantially confirmed | Confirmed |
| Revise Project's Outputs | Not envisaged at this stage | Power output unmodified. Schedule of second stage power supply (units 5-8) to be assessed. | Power output unmodified. Sequence for putting in operation the Unit shall be independent from the original two stages power supply. | Power output unmodified. Unit commissioning sequence: U1 (Dec20), U2 (Apr21). Other units still to be defined. |
| Revise Project's Purposes | Not realistic | | | |
| Project re-engineering | Addition of Middle Level Outlet (MLO) essential | | Future decision on the MLO to be supported by a Potential Failure Modes Analysis. | PFMA workshop carried out. To be further developed to achieve a risk-informed decision on the additional MLO. |
| Partial/ total retirement | Very unlikely, unless cavern location must be abandoned for excessive damages. | Partial retirement can be excluded. | Partial retirement excluded. | |
| Long-term vision | Project will have to be decommissioned at the end of its useful life, when coarse sediment management, to sustain run-of-river operation, will no longer be economical. | Bathymetric surveys should be initiated to assess sedimentation trends. | Long-term reservoir management retains its importance. | IAP would like to review results of bathymetric surveys carried out to date. |

### 1.4 Project's Risk Register and Emergency Preparedness Plan

The Project's Risk Register covers all types of risks: safety, technical and financial. In some risk analysis, an overall risk index is estimated, using a combination of the three types, with some sort of weighting factors. Such overall indexes can be misleading if the aggregation procedure is not understood. In other words, the types of risk should be disaggregated according to the type of risk assessment one is interested in.

The document titled "Alertas Proyecto Ituango", reproduced in fig. 1, is a good synthesis of the key elements to assess the Project conditions in real time in the interest of the safety of the Project and of downstream communities. As such, it represents a key component of the Project's Emergency Preparedness Plan.

| Alertas Proyecto Ituango | | | | | | | |
|---|---|---|---|---|---|---|---|
| Reporte CMT: 25/11/2019 | Hora de Corte: | 5:00 p.m. | Valores de Referencia para alertas | | | | Observaciones |
| RIESGOS | Medida | Variable | Estado | Normal | Amarilla | Roja | |
| Caudal | Caudal Pintada | (m3/s) | 875,84 | <1500 | >1500 | - | Registro tomado a las 4:15 p. m. |
| | Caudal Olaya | (m3/s) | 1151,26 | <2000 | >2000 | - | Registro tomado a las 4:30 p. m. |
| | Caudal que ingresa al embalse | (m3/s) | 1253,67 | <10000 | >10000 - <20000 | >20000 | Registro tomado a las 5:15 p. m. |
| | Vertimiento | (m3/s) | 1117,98 | - | - | - | Registro tomado a las 4:30 p. m. |
| | Descarga Ituango | (m3/s) | 1169,51 | - | - | - | Registro tomado a las 4:30 p. m. |
| | Puerto Valdivia | (m3/s) | 1265,78 | <2400 | >2400 - <3400 | >3400 | Registro tomado a las 4:15 p. m. |
| Presa | Piezómetros | Estado | Estable | Estable | En observación | Inestable | Valor esperado con relación a la variación del nivel del embalse. |
| | Celdas de presión | Estado | Estable | Estable | En observación | Inestable | Valor esperado relacionado al empuje ocasionado por la variación del nivel del embalse. |
| | Asentamientos | Estado | Estable | Estable | En observación | Inestable | No se presentan novedades |
| | Nivel de Embalse | (msnm) | 407,45 | <422 | >422 - <432,5 | >432,5 | El nivel del embalse disminuyó -0,01 m en las últimas 12 horas. |
| | Infiltraciones lleno prioritario | (l/s) | 8,13 | <79 | >79 - <100 | >100 | Este dato corresponde al total de las infiltraciones registradas en los llenos de la Presa, asociadas a cuatro franjas diferentes. |
| | Infiltraciones Margen Derecha | (l/s) | 25,02 | <121 | >121 - <407 | >407 | La totalidad del agua infiltrada en el estribo derecho se afora en la Galería 265_MD. Se reporta el dato del 19/11/19. |
| | Infiltraciones Margen Izquierda | (l/s) | 64,52 | <120 | >120 - <219 | >219 | El valor corresponde a la suma de las infiltraciones que se presentan en las galerías 250+313+380. Gal 250 presenta aumento por fuga de agua en tubería instalada sobre el hastial. |
| Deslizamientos | Volúmen de desplazamiento taludes captación | (m3) | 0 | < 250.000 m3 | >250.000 m3 | >400.000 m3 | Se presenta tendencia lineal en 1 pixel en la zona A1 Suelo con velocidad cercana a 6,74 mm/h. Registro tomado a las 04:00 p.m. |
| | Volúmen de desplazamiento talud cercano a vertedero | (m3) | 0 | < 250.000 m3 | >250.000 m3 | >400.000 m3 | Deformaciones no significativas. Registro tomado a las 04:00 p.m. |
| | Volúmen de desplazamiento portal desviación | (m3) | 0 | <250.000 m3 | >250.000 m3 | >400.000 m3 | Se presenta tendencia lineal en 2 pixeles en la zona B2 con velocidad cercana a 6,16 mm/h. Registro tomado a las 04:00 p.m. |
| Movilidad Túnel Vial km 12 | Deformación de la Sección | Estado | Estable | Estable | En Observación | Inestable | No se presentan novedades, vía habilitada |

*Fig. 1: Early warning system: monitoring and warning levels*

The IAP understand that the early warning system in fig.1 is the result of a broader risk analysis carried out by the Designer and other technical parties, which of course adds value to the system. Having said that, the IAP offers the following suggestions to improve the system in terms of effectiveness and communication with stakeholders.

- The spillway's discharge should be added to the level of alert because, while a discharge value can be perfectly safe for the dam, it could have significant consequences downstream. Based on the other discharge values indicated as thresholds, EPM may want to consider, and adapt as necessary, the following limits:

| Nivel de Alerta | Normal | Amarillo | Rojo |
|---|---|---|---|
| Vertimiento ($m^3/s$) | < 2000 | > 2000; < 3000 | > 3000 |

- In the case of "Deslizamientos", the early warnings system uses the volumes of potential mass movements as the indicators. That is acceptable but does not constitute an "early" warning. To achieve that, the system should also include elements from key monitoring instruments (inclinometers, extensometers, piezometers, pressure cells). As indicated for the Dam, "Estable", "En observacion", "Inestable" could be the definitions that trigger the three alert levels.

## 1.5 Permanent plugging of TD2 and GAD

Both sliding gates of the GAD have been successfully closed and a temporary by-pass realised to lower the reservoir pressure and increase safety during the construction of the final plug. The situation is under control and the IAP expects that the final plug can be successfully and safely built.

Closure of the TD2, the second waterway to be plugged, faced further delays due to the poor quality of the steel pile grid, which represents the first essential step in the treatment. EPM is acting to improve the steel quality.

The IAP noted that a detailed action plan is in place to bring the issue to closure. It features:

- Procurement of better-quality steel for the pile grid,
- Attempts to grout voids in the temporary plug by means of grouting[1],
- Resumption of steel pipe installation,
- Launching of the plastic spheres and proceed accordingly to the sequence which has been optimised with hydraulic model test.

The plan includes contingency measures such as grouting, increasing the pile grid density, pump out most of the throughflow to allow safe entrance of work-force, etc.

The IAP recognizes the complexity of the operation and believes that, under the unprecedented circumstances, planning is fully satisfactory, and the technological measures being adopted are appropriate. Satisfactory contingency planning is also in place to overcome unforeseen developments.

### 1.6 Level of Downstream Hazard

The above described early warning arrangements are based on a monitoring system operated 24 hours a day, 365 days a year. The system controls 650 instrumentation and monitoring signals in real time. Three laser radars and several video cameras for remote surveillance integrate the system. Each work site has got instruments to measure seismic, geotechnical, hydraulic, and other types of parameters. All is unified in the Technical Monitoring Center (CMT).

The alert condition for the downstream population is still at yellow-level and will remain such until the GAD and DT2 are definitively plugged. Comprehensive monitoring provides confidence that safety is under control. Figure 2 below is a case in point. It shows the water velocity through the DT2, in real time.


*Fig. 2: Water velocity in the right diversion tunnel (DT2): real time monitoring*

Any change in the velocity pattern would signal a potential deterioration of the existing plugs and the early warning measures could be adopted.

[1] That grouting must be done in presence of some 7 m3/s water flow, which is indisputably very hard to achieve. The Designer is attempting it anyway, and the use of sleeved pipes *(tube-a-manchette)* is planned which could possibly improve effectiveness.

### 1.7 Safety Assessment

The last IAP's visit to the Project took place in October 2019. In the May 2020 Virtual Mission, Project staff provided a comprehensive description of the ongoing works. Availability of real-time video cameras, installed at key locations, significantly helped appraising the conditions of the works.

The main safety-related aspects of the Project can be summarised as follows.

- The level of instrumentation and monitoring of the Project is state of the art: all readings are automatic, centralised to control room, and remotely accessible.
- Performance of the dam is in line with design expectations and correspondence between predicted and as-measured performance is excellent.
- The treatment of the area above the diversion tunnels remains to be defined.
- A mass movement is in progress, in an area away from the works, and does not represent a threat for the reservoir; the zone is monitored to define the needed interventions.
- The spillway is operating full time, which is beyond the design assumptions, and will continue so until turbine operation will be established. Monitoring of the plunge pool slopes does not show any sign of unacceptable distress.
- Most of the underground areas, which were affected by uncontrolled river throughflow, have been inspected and needed repair works defined. The large cavity between pressure shafts 1 and 2 has been successfully backfilled.
- Of the remaining works, required to commission units 1 to 4, stabilization of the collapsed area between PH Cavern and Almenara 1 is the more challenging; the experience acquired on the successful filling of shafts 1-2 cavity will help the conduction of the works.
- The South part of the Cavern and related waterways is geotechnically more problematic; extensive treatments are planned.

In conclusion:

- Despite the unprecedent events that impacted the Project, the undertaken works allow to express a satisfactory assessment on the safety of both surface and underground works.
- Plugging the DT2 remains the most urgent activity and EPM is concentrated on that. Once that is successfully completed, the safety conditions for the population downstream will return to normal.

## 2 GEOTECHNICAL ASSESSMENT

### 2.1 Pressure Shafts 1 to 4 (North side)

During the IAP site visit in March 2019, the size of the cavity connecting shafts 1 and 2 had been preliminary outlined, and repair works under definition. It was feared that the collapse had created a loose and unstable rock mass at its boundary. Fig. 3 shows the March 2019 forecast and the now safely backfilled cavity.

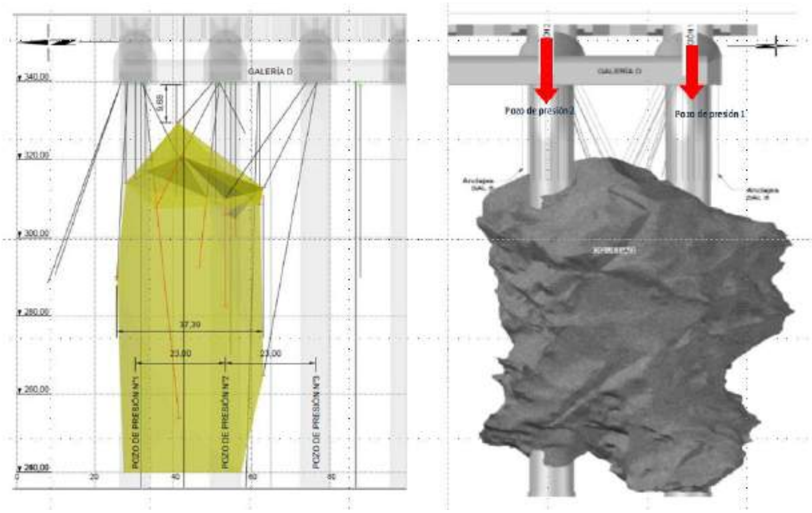



Fig. 3 *Cavity between pressure shaft 1 and 2. March 2019 forecast (left) and April 2020 as built.*

Cavity stabilization and backfilling (60,000 m$^3$) has now been successfully completed. Remarkably, contrary to last year's expectations, the rock mass at the boundaries of the cavity was found in good conditions. Monitoring did not show signs of noticeable deformations of the cavity boundary. The backfill will act as a stiffening element and maintain the long-term stability of the rock mass in this area.

Minimum, localized seepage was observed during the works. Drilling for contact grouting and control boreholes showed satisfactory results, and low grout absorptions. A few additional control holes are planned.

The lower parts of the pressure shafts to units 1,2,3,4 have not yet been inspected. In case they are found to need major repairs, those might affect the completion plan.

### 2.2 Pressure Shafts 5 to 8 (South side)

Many boreholes were drilled in the «disturbed rock mass (DRM)» above the upper elbows of the shafts. The first impression one gets, based on RQD values, is that some cores indicate a very disturbed rock mass. The IAP is of the opinion that large parts of the cores were severely affected by the drilling bit's action and by their extraction from the barrels. Very likely, the actual quality of the rock mass is much better.

Fig. 4 provides the rationale for the IAP opinion. The structure of the rock mass (joints and discontinuities) is recognizable in the left box. That is not the case in the right box where core ruptures are perpendicular to the borehole axis; that feature characterizes a sampling which is not representative of the in-situ conditions of the rock mass. The cores in the right box are clearly affected by the drilling process and by the extraction of the cores from the barrel. As such those cores are not representative for deriving rock mass quality indexes.

*Figure 4 Representative (left) and non-representative (right) coring.*

An extensive campaign of boreholes and grouting has been carried out in the area (see Fig. 5). From the information provided, the IAP is not sure that voids exist in the upper part of the shafts. In the lower part of the shafts, voids are reported to exist, but the examined borehole data do not permit to confirm that. In any case, the information collected should be adequate for a detailed characterization of the rock mass.

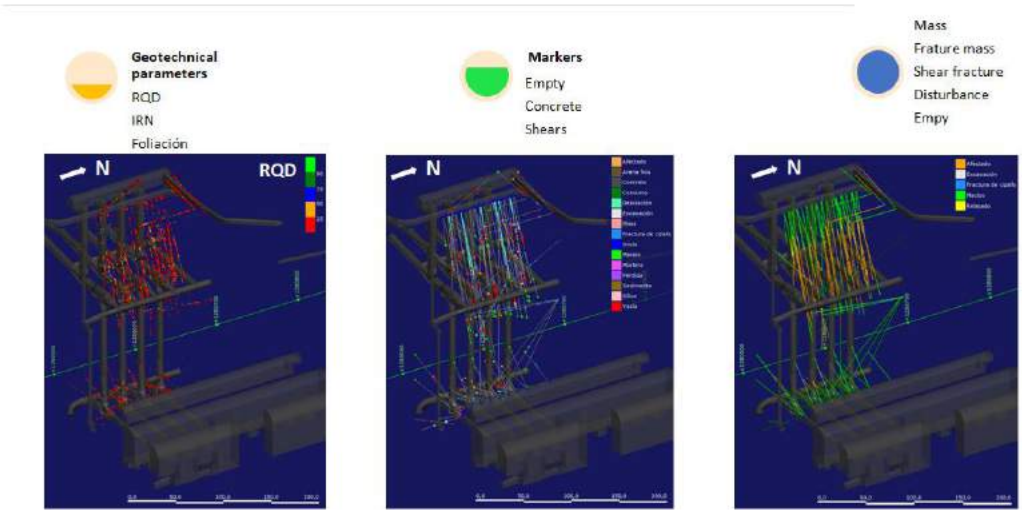



*Figure 5 Exploration campaign South zone. Shafts 5 to 8*

The IAP recommends preparing a zoned classification of the rock mass, giving due consideration to the reliability of the cores. The GSI method could be used for that purpose. The design of rehabilitation works should be based on actual rock mass defects (open joints, shear zones, loose rock, cavities etc.) and associated potential mechanisms of failure.

In terms of rock mass treatment, consolidation grouting is certainly anticipated. Based on the photos of the borehole cores, the rock mass is appropriate for grouting.

## 2.3 Powerhouse Cavern Complex

Despite the extremely high and uncontrolled energy dissipation that occurred underground, for a long time, overall rock-mass behaviour is satisfactory. Remarkably, no progressive failure due to stress re-distribution has been observed.

Based on the data so far available, rock mass permeability is expected to be low. The interior of the rock mass surrounding the caverns is expected to be tight. There is negligible water infiltration in the Powerhouse (PH) cavern; in spots only, not more than 2 l/s have been measured. Piezometric observations are extremely important to detect possible hydraulic connections with the reservoir. The Designer should consider whether more piezometric installations are required.

The main fault Mellizos, crossing the PH cavern in the center, E to W, does not seem to have aggravated rock falls/erosion. Some disturbance, possibly associated to Mellizos fault, is noticed only in tail race 2.

The major underground openings are fully instrumented (fig. 6). Most extensometers and other instruments show stable trends, indicating that the interior of the rock mass is not disturbed.

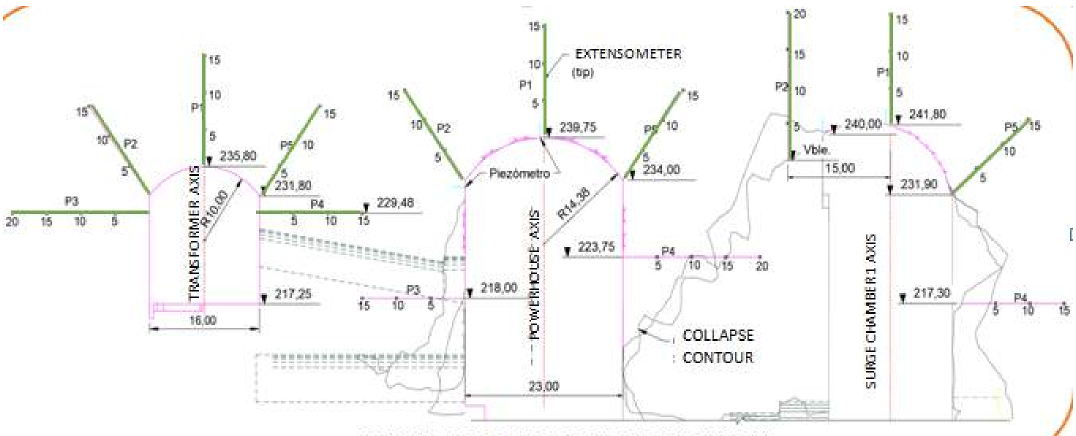



*Figure 6 Powerhouse complex. Multipoint borehole extensometers*

In few places slight deformations have been recorded. Reportedly, the largest displacements (5mm) have been recorded at specific locations where major interventions took place. That is evident from the orange line in fig. 7.

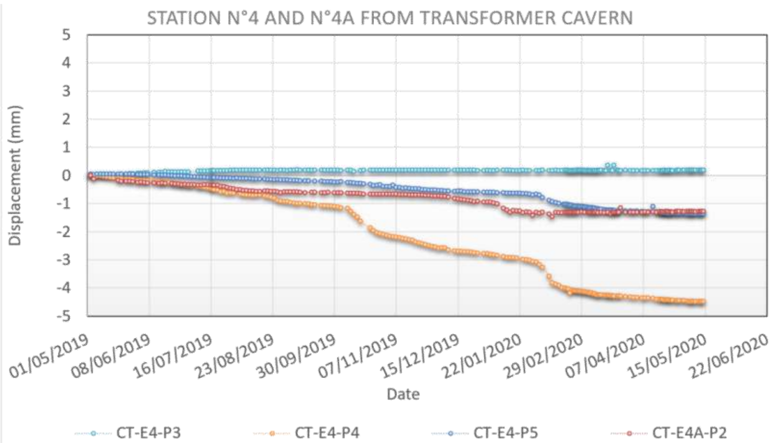



*Figure 7. Multi-Point Borehole Extensometer reading, where some displacement reached 5mm.*

Such movements, albeit small, go beyond the level of instrument's accuracy, therefore an increased monitoring frequency should be adopted in case those displacements would not show sign of stabilization. Obviously, monitoring should continue everywhere.

The Transformers cavern is fully mapped and mostly stabilised. The north side of the PH cavern has been stabilised. The major ongoing activity is the treatment and backfilling of the large (40,000 $m^3$) collapsed zone between PH cavern and surge chamber (Almenara) 1.

The Consultant has carried out calculations of structural wedge failure and numerical stress analysis of the PH complex. Representative excerpts are shown in fig. 8 and fig. 9 respectively.

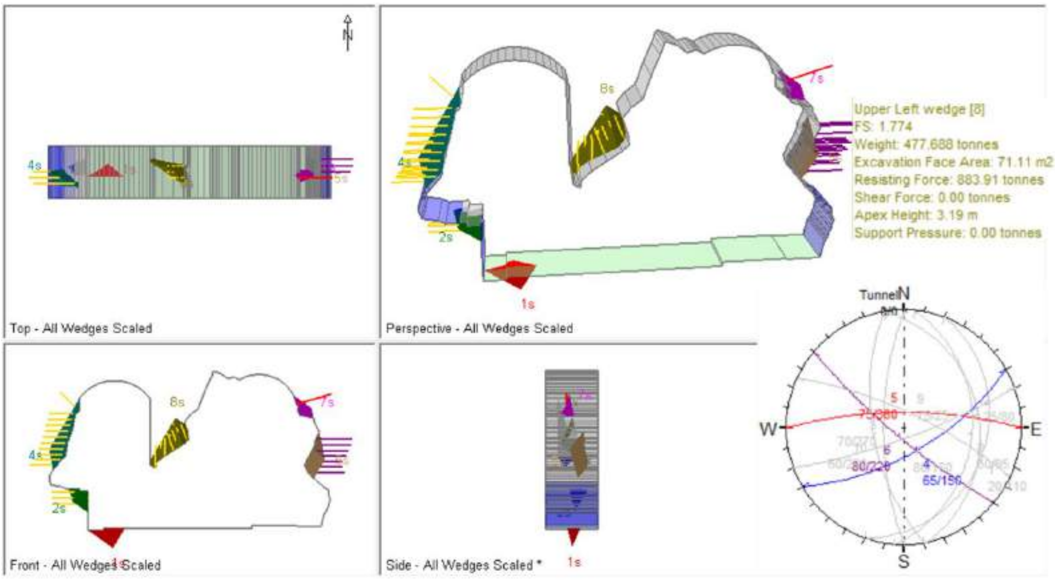



*Figure 8: PH complex wedge analyses*

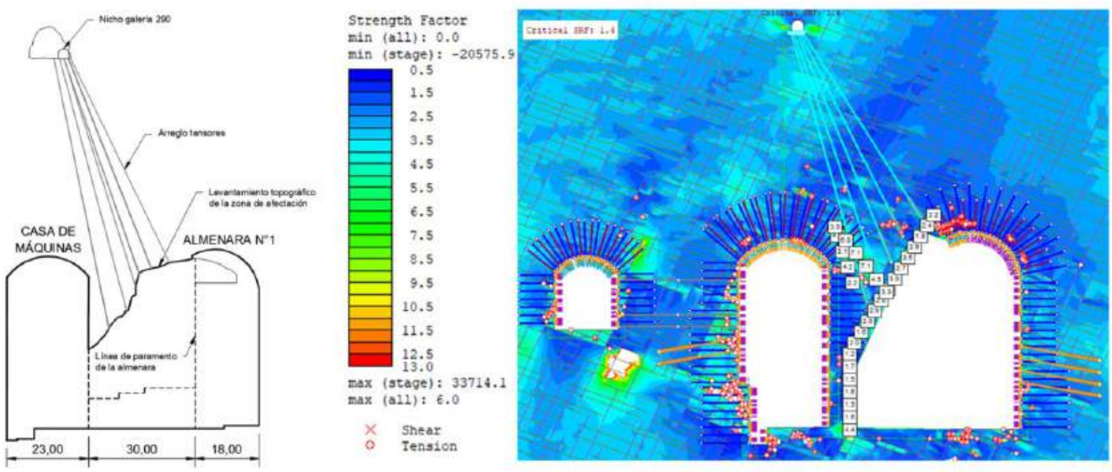



*Fig. 9: PH complex Stress Analysis*

The analyses model the current geometry of the excavations and the applied support / reinforcement measures within a jointed rock mass. The resulting safety factors are satisfactory. To evaluate the results of this analysis, the IAP would like to review the basic assumptions, with particular reference to the topics listed in the following table.

| |
|---|
| Rock mass parameters (strength and deformation) assumed in the model |

| |
|---|
| Joint pattern and strength, rock structure and strength in the zone adjacent to the openings and away from them. |
| Assumptions regarding disturbance factor close to the disturbed walls of the opening are very important, especially around the collapsed area and within the thin pillar between the Powerhouse and Almenara No1. |
| Numerical analysis staging. Description of stages from the initial conditions to the final modelling stage. |
| Modelling of the support measures at the time of the failure events. |
| Strength reduction factor process. Description of critical failure mechanism as per the results of the model, assumption of elastic or plastic response of support, consideration of SRF estimation for stages earlier than the final one to investigate potential intermediate stages of the rehabilitation process with lower levels of safety. |
| Postulated treatment / strengthening measures in the lowest, thin part of the pillar between the Powerhouse and Almenara No1 (see fig. 9). |
| Wedge scaling assumptions. |

The rehabilitation design foresees reconstructing the Almenaras with concrete backfills, after rock mass reinforcement. The backfill will be particularly massive in the case of Almenara 1 and the build-up of water pressures could be destabilizing, especially in consideration of the oscillations in the surge chamber. The IAP recommends that the Designer assesses the need of drainage holes: Fig 10 shows a notional layout.

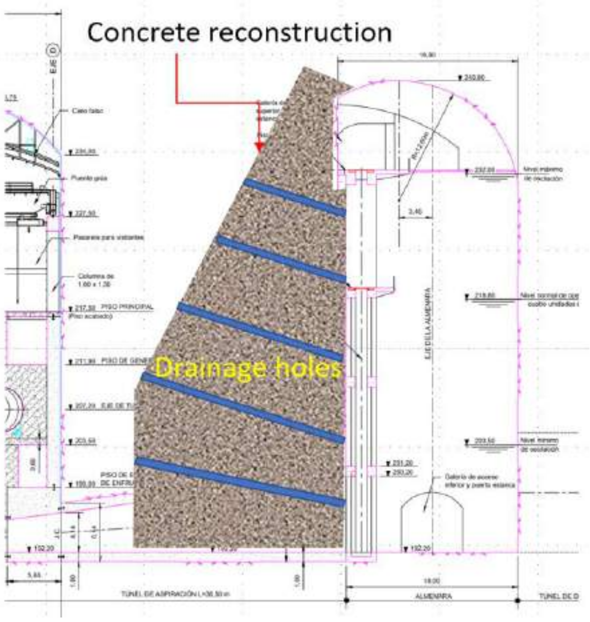



Fig 10 *Drainage to massive concrete reconstruction of Almenara 1.*

As indicated by the boreholes drilled in the area, the South zone of the cavern complex is geotechnically more problematic. The rock mass is more jointed and less homogeneous compared with the North zone (units 1 to 4). Extensive grouting treatments are planned. Some voids are expected in the area between the construction galleries, the Powerhouse and Almenara 2.

Tailrace tunnels are reported in fairly good conditions.

The underground complex features a maze of temporary and permanent galleries, some of them may induce hydraulic gradients towards permanent openings. A Plugging Plan is necessary to carefully sequencing plugging, lining and grouting works. Management of the risk associated with the reservoir head should inform the Plan to avoid hydraulic fracturing, drainage plugging, damage to permanent linings, etc.

### 2.4 Intermediate Discharge Gallery (IDG)

Difficulties of opening the IDG intake, under 140+ m water pressure, have led to the decision to off-take water from higher elevations, along the power intake waterways.

Based on prudent engineering judgement, the Designer does not favor the original option of sinking a shaft between power conduits 3 and 4.

IAP believes that the attitude is not necessarily substantiated by empirical data (permeability, piezometric levels, direct contact with reservoir), but appreciates the cautionary approach. Besides, the Designer may want to recommend additional piezometers to signal potential increase of hydraulic gradients between the reservoir and the waterways.

Having said that, the IAP appreciates that schedule arguments are critical for reaching an informed choice among the contemplated alternatives. For example, Option 7 would require a detailed hydraulic study of the offtakes from the power shafts, steel material shall be procured soon, the “branching” should be installed at the same time of the penstock, and a large span opening would be needed for assembling the steel branch.

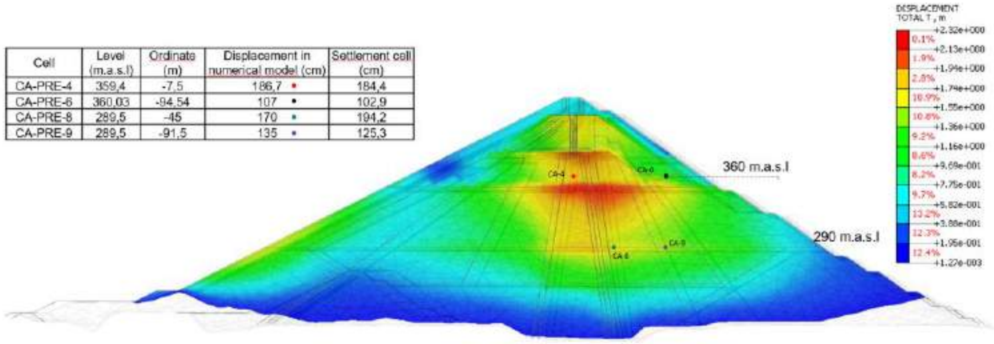
Based on the above, IAP supports option 5. In the tunneling portions of the IDG, where weak rock is encountered, it will be essential to install a full circular lining.

The IAP points out that, during the life of the project, it could become valuable to flush sediments in the area of the intakes and prolong the life of the project. To that effect, the need to open the IDG intake at el. 260 may be reconsidered, during the life of the Project. Planning should be based on bathymetric surveys. In advance of its next visit, the IAP would like to review the surveys carried out to date.

### 2.5 Dam

The monitoring system reveals a convincing response of the dam body, in terms of deformation and seepage trends.

Settlements are possibly lower than expected, especially in consideration of the haste in which the upper part of the embankment had to be completed. Settlements are very small in comparison to other dams of this type and height. Rate of settlement is currently 0.1-0.2mm/day, which is satisfactory.



| Cell | Level (m.a.s.l) | Ordinate (m) | Displacement in numerical model (cm) | Settlement cell (cm) |
|---|---|---|---|---|
| CA-PRE-4 | 359,4 | -7,5 | 186,7 | 184,4 |
| CA-PRE-6 | 360,03 | -94,54 | 107 | 102,9 |
| CA-PRE-8 | 289,5 | -45 | 170 | 194,2 |
| CA-PRE-9 | 289,5 | -91,5 | 135 | 125,3 |



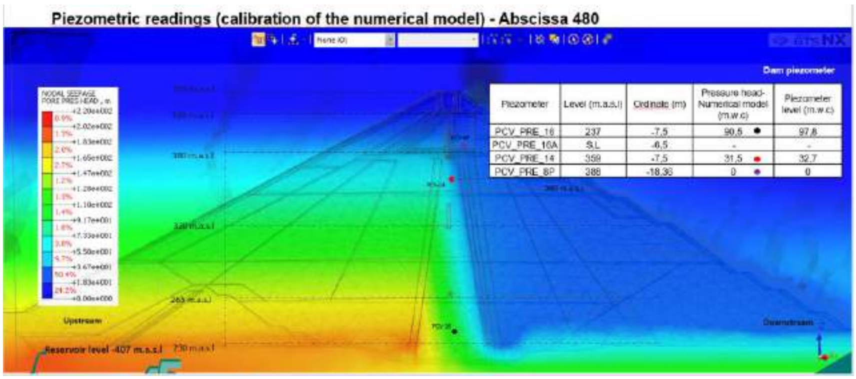
*Figure 11. Settlement cells (calibration of the numerical model) - Abscissa 480*

The behaviour of grout curtain is reportedly satisfactory. The IAP would like to review the piezometric data downstream of the curtain, and the drainage records.

Results of the grouting works, which have reached a progress of 90%, are satisfactory. During the IAP September 2019 visit, leakages at the left side amounted to 170 l/s at the level of the low gallery. Presently, they have reduced to 32 l/s. They are even lower in the central and right side.

The behaviour of the core and plastic zone is satisfactory. The seepage through the upper part of the dam is about 6 l/sec only. The positive effect of the diaphragm wall is evident**.** The area has been designated "priority embankment" because its construction had to be accelerated, with a modified design layout, during the 2018 emergency. Given the observed performance, that area should be considered "definitive filling".

As shown in figures 12 and 23, a particularly good correspondence exists between calculated and measured values of deformations and piezometric levels.





| Piezometer | Level (m.a.s.l) | Ordinate (m) | Pressure head-Numerical model (m.w.c) | Piezometer level (m.w.c) |
|---|---|---|---|---|
| PCV_PRE_16 | 237 | -7,5 | 90,5 | 97,8 |
| PCV_PRE_16A | S.L | -6,5 | - | - |
| PCV_PRE_14 | 359 | -7,5 | 31,5 | 32,7 |
| PCV_PRE_8P | 388 | -18,36 | 0 | 0 |

*Figure 12: Piezometric readings (calibration of the numerical model) - Abscissa 480*

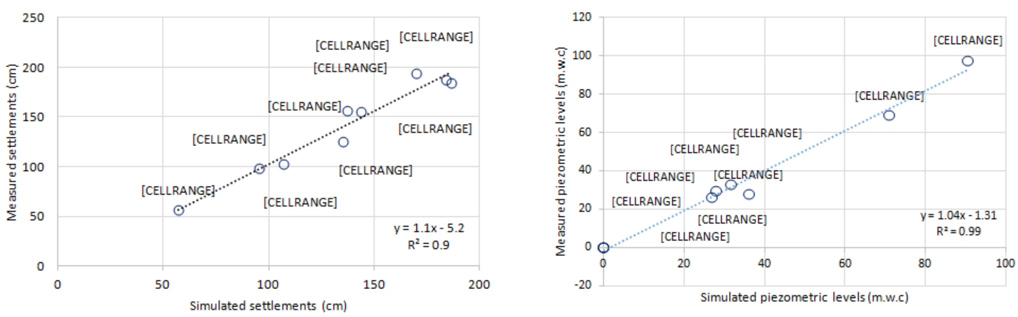




*Figure 13:  Numerical model vs readings of the instruments - Calibration*

## 2.6 Spillway pool

The delayed entrance in operation of the power plant forces the spillway to operate continuously.

With flows lower than 1,000 $m^3/s$, the water jet would impinge on the rock slopes. To avoid that unfavourable condition, low flows are discharged through the narrow chute on the left side of the spillway. The measure is working well. The need to seal the floor-level connections between the left side chute and the main one is acknowledged by EPM, and appropriate actions are being taken.

The plunge pool's geometry is designed to perform over the life of the project, and there is no evidence of abnormal conditions developing. The overall stability does not show any evident signs of concern. However as already mentioned in the 2nd report of the panel, the slopes above the plunge pool area are saturated by the mist and stressed at their toes. That has already caused some minor failures, which will inevitably progress in time. This is an expected condition for this type of energy dissipation design. The IAP concurs with the monitoring programme of the plunge pool's slopes and surroundings, which should be permanent.

To evaluate the potential effects that the slopes could suffer, erodibility and geotechnical stability analyses are being carried out. They are based on the energy of the water jet and the geotechnical properties of the massif found during excavation. The IAP agrees with the performance of this analysis. From existing data, the rock mass at the pool is sound with few main discontinuities.

When, with turbine operation, access will be possible, a thorough assessment will be done and the opportunity to pre-excavate parts of the pool evaluated.

## 2.7 Slope stability of the right abutment

Instrumentation shows overall satisfactory performance of the slope over the power intake platform.

The static analyses of local (superficial) and global (deeper) sliding surfaces indicate acceptable factors of safety. The strength parameters used (Fig 14) are rather on the conservative side. Groundwater conditions appear different in the two adjacent cross-sections presented to the IAP (Fig 15). In section A, the assumed water table is quite close to the surface. Certainly, a conservative assumption, given ground water level observed in the section of site 7, slightly to the north. In section B, no water table is visible.

| Material | Color | Densidad ($kN/m^3$) | Criterio | Cohesión ($kN/m^2$) | Phi (°) | UCS ($MN/m^2$) | GSI |
|---|---|---|---|---|---|---|---|
| Qv | | 18 | Mohr-Coulomb | 20 +/-5 | 30 +/-10 | - | - |
| IIA Fracturado | | 23 | Hoek-Brown | - | - | 40 | 25 |
| IIA | | 24 | Hoek-Brown | - | - | 70 +/-10 | 48 +/-12 |
| IIB | | 26 | Hoek-Brown | - | - | 80 +/-10 | 50 +/-12 |
| Cizalla | | 16 | Mohr-Coulomb | 10 | 25 | - | - |

*Figure 14: Stability analysis – Geotechnical parameters*

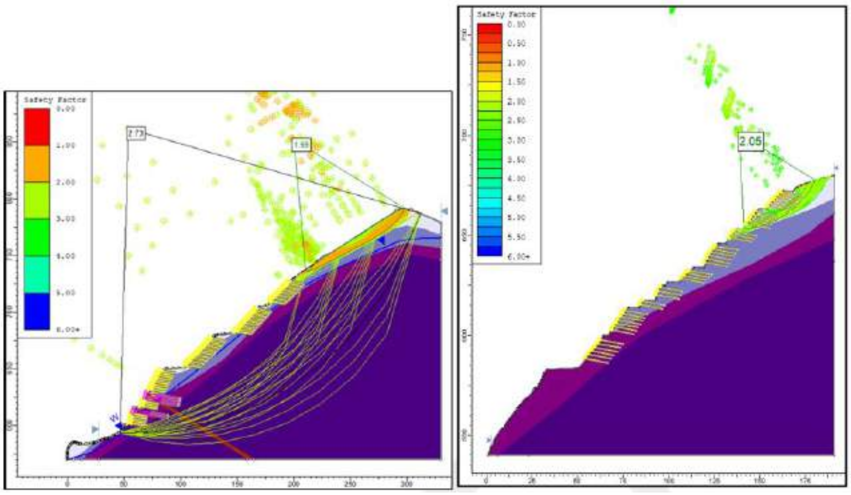



*Figure 15: Static slope stability analysis. Left: Cross section A. Right: Cross section B*

Some cracks have appeared on the upper parts of the slope. Of these, the cracks in Zone 1 do not necessarily agree with the results of stability calculations and may need to be reconsidered in modelling the slope (e.g. tension cracks).

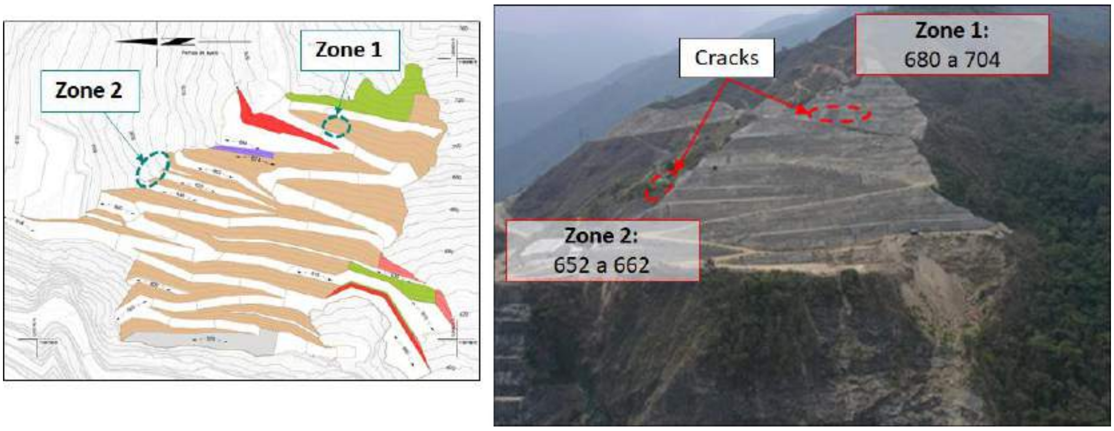



Figure *16: Power intakes- Localized cracks in the upper part of the slopes*

The other cracks are generally localised fissures in the shotcrete, which are most probably associated with slight changes of rock mass weathering, boundaries/ discontinuity of shotcrete treatment and consequent differential movements. Drainage holes in shotcrete are obviously an appropriate measure and probably will have to be increased in number.

The treatment of the Romerito sink hole will be the next step; surface drainage, reinforcement of the cavity rim, and back filling are among the considered measures.

The effectiveness of the executed drainage gallery at the northern slope side is not clear to the IAP. Apparently, it is in relation to Site 7 slopes, at the North margin of Romerito's treatments. Besides, the gallery is located above the assessed water table. The perched water table, above, looks insignificant. Anyway, drainage is always useful in slope stability and the IAP has no specific recommendations.

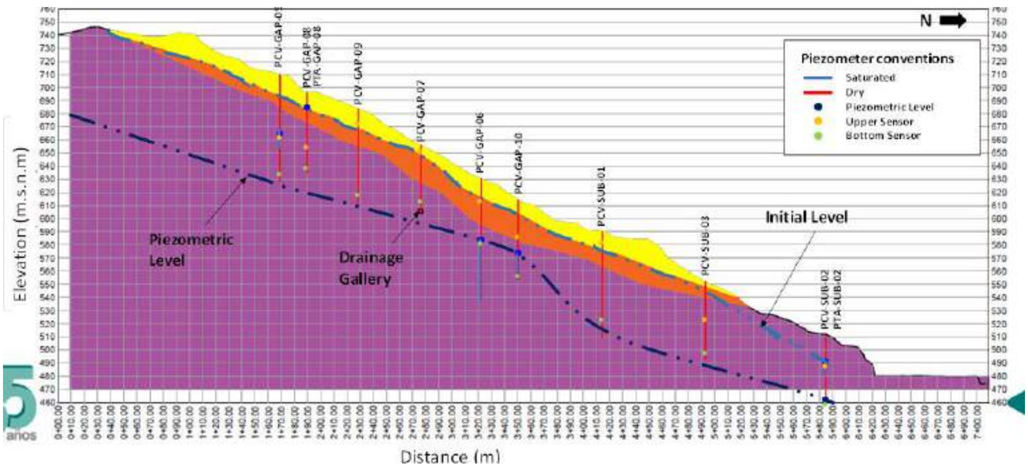


*Figure 17: Drainage gallery – Piezometers. Site 7*

Inclinometer measurements in the area, indicate a pattern of displacements /fig. 18) that does not correspond to a recognizable sliding surface at any level. No abrupt changes of slope are visible along the inclinometer alignments. Most probably, the recorded movements result from incomplete or defective fitting of the inclinometer's tube in the drill holes.

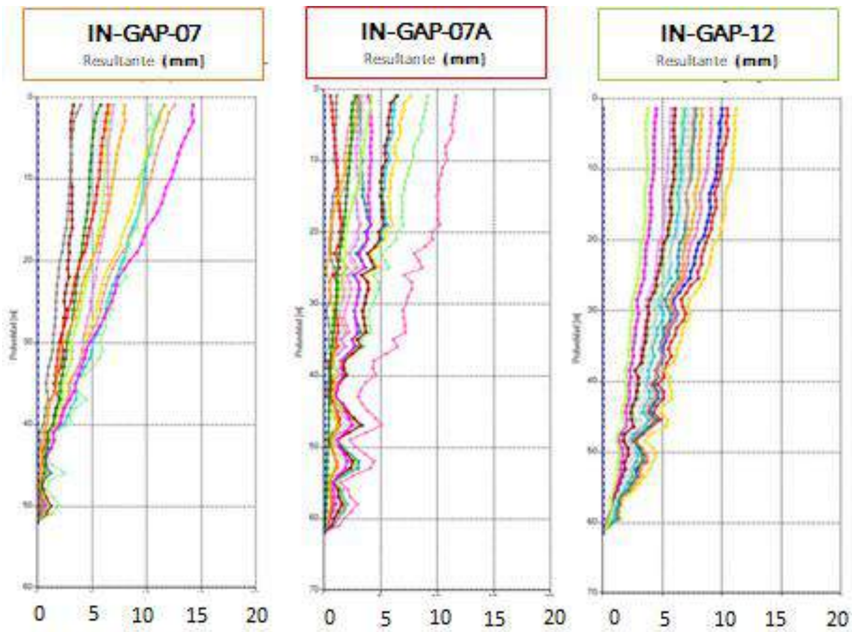


*Figure 18: Inclinometer readings in the slope over the platform of gates. The curves do not evidence any deformation or rupture of the inclinometer tube.*

### 2.8 The slope further upstream to the south of Romerito

EPM informed that, after the treatment works in the Romerito area are completed, the design of slope stabilization works in the upstream southern areas will be re-assessed. The present evidence is that this upstream area does not show any of retro or lateral evolution.

*Figure 19: The destabilized area above the two diversion tunnels. In the far upper end the slopes of Romerito, before the reshaping and treatment*

The issue has been raised in all IAP reports. A slope in those conditions cannot be left behind untreated. It is too close to the dam, and we cannot preclude the possibility of completing the IDG or even adding an MLO during the life of the Project.

### 2.9 Other slope stability features

On the left reservoir slope, near the dam site, two instabilities occurred, one at 0+900 to 1+290 and the second at 2+255 (fig. 20). The first case affects the alternative road. The IAP has neither been involved on these slides, nor visited the sites.

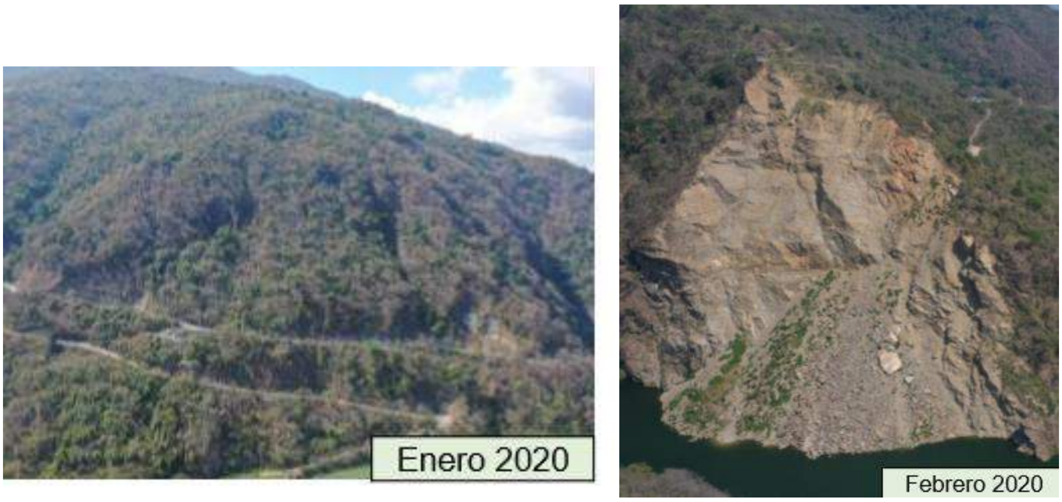



*Figure 20: Instabilities near the complex of the project, at the left side, over of the reservoir, Left, at 0+900 to 1+290 and right at 2+255*

Looking at the photographs and sections, the 0+900 to 1+290 landslide is clearly a rotational one. The rock is probably the weathered and distressed zone of the upper part of the gneiss formation. The surface of the slide, as shown, is not deep. Slope reinforcement with anchors is considered reasonable for protection of the road. Surface drainage, with catchwater drains, and possibly slope drainage holes should be considered. More detailed observations would require a site visit and review of the stability analysis.

In its April 2019 Report, the IAP commented on slope stability conditions over the reservoir's rim. The IAP was not informed of new events that require updating the April 2019 observations, which are briefly recalled in the following.

*"No geomorphological features denoting major old landslides were recognized. The hydrographic features are also reassuring. Generally, the slopes exhibit stable overall configurations. In the upstream part, the basin' slopes present erosion landforms. These forms indicate a stable background in terms of slope retention. They cannot generate significant landslides. Erosion is reduced in the downstream part of the basin, probably due to the hardness of the bedrock. Again, no feature of large-scale mass movements is detected.*

*Landslides of reduced size and small scale, either rotational or planar, are observed in places and new ones may be generated by the operation/ fluctuations of the reservoir. They cannot generate waves of concern.*

*Existing studies hinted at the possibility of an old mega slide, 50km upstream of the dam site, at the left side of the reservoir ("Guasimo" mega slide). No strong evidence was observed in the geomorphology and features of the area. There is no well-defined morphology of an old escarpment from where the landslide might have originated. Heavy erosion is present denoting overall stability of that escarpment area. The size of the downhill mass supposed to have slid, is not compatible with the uphill morphology. The whole area is characterized by persisting erosion."*

# 3 ELECTRICAL AND MECHANICAL EQUIPMENT

## 3.1 Equipment installed in the cavern complex

During the May 2020 virtual mission, the IAP was enabled to observe, by remote cameras, the conditions of and the ongoing activities in the following areas:

- North shaft chambers (the same north shaft chamber and the south shaft chamber were visited in September 2019),
- Powerhouse cavern mainly in its north part (the same part was physically inspected in September 2019 while the south part was at that time filled with debris), and
- Transformer and cable galleries (both extensively visited in September 2019).

A complete assessment of the damages to most of the electromechanical equipment was already available in September 2019 and it was confirmed during the May 2020 virtual mission.

All the equipment already installed, including the mechanical parts embedded in concrete in the powerhouse's North area, are now considered unsuitable for future operation. This assessment also applies to the step-up single-phase transformers and HV cables, the only components for which a possible recovery was not ruled out in principle.

Their physical and functional damages were not drastic. However, an EPM/Insurers joint survey decided for a complete replacement, mostly at Insurers cost; response by the Insurances was positive and EPM privileged a conservative approach.

Such decision appears cost and risk effective for EPM and, under the conditions, is fully supported by IAP. Besides, it must be added that the transformers' manufacturer (SIEMENS) would have not extended a guarantee for any equipment if not fully replaced.

The transformer's oil tanks were unaffected and various assessments by EPM did not report any losses of oil (see fig 21). Oil was subsequently removed from the transformer tanks and properly disposed.

*Figure 21: single phase transformer[archive]*

At the time of the May 2020 virtual visit, the transformers were still in place. The activities of the company that purchased them as scrap material are on hold due to Covid-19; however, a team of 60 persons of EPM is working to dismantle the transformers.

EPM has in its warehouses 6 out of the 25 single phase transformers of the original supply, which are enough for the first two units. The other 19 are already procured and their delivery schedule is: 6 in the second semester of 2020, 6 in the first semester of 2021 and 7 for the second semester of 2021. Transformers are not on the critical path.

11 HV single phase cables already procured and their deliver to site is expected by the end of 2020. They are not on the critical path.

*Figure 22: HV single phase cable[archive]*

The two overhead traveling cranes are still in place but unsuitable even for temporary activity. The 2 x 300 tons new overhead cranes are already procured; their manufacturing shall be completed within June 2020 and their delivery to site is expected for August / September 2020. Their delivery schedule will not directly impact the project schedule because EPM is using mobile cranes in the meantime (see fig. 23).

*Figure 23: The second crane at work in the southern part of the powerhouse*

At the time of Powerhouse flooding, the progress of the installation of the north side turbines was well advanced, especially Unit 4 and 3 that were to be commissioned first.

The lowest parts of units 1 and 2 and the corresponding first and second phase concrete were assessed to be completely unsuitable for any remedial action. The same assessment was extended to units 3 and 4 at the end of 2019. Rehabilitation of units 1 to 4 has therefore started from first phase concrete (see fig 24).


*Figure 24: Removing Unit 3 and 4 equipment as scrap material*

As a result of the negative assessment of unit 3 and 4, EPM decided to go back to the original sequence for commercial operation, proceeding sequentially from 1 to 4. IAP supports the decision that appears the fastest in terms of logistic.

The situation of draft tubes' embedded parts and other components is as follows:

- The entire supply for unit 1 is available on site.
- The supply for units 2,3 and 4 is already procured.
- Part of the supply for units 5 to 8 (south PH) are available in the warehouse.

Fig. 25 shows the erection progress of the draft tubes of units 5 to 8, at the time of flooding the powerhouse (green: installed; red: to be installed).

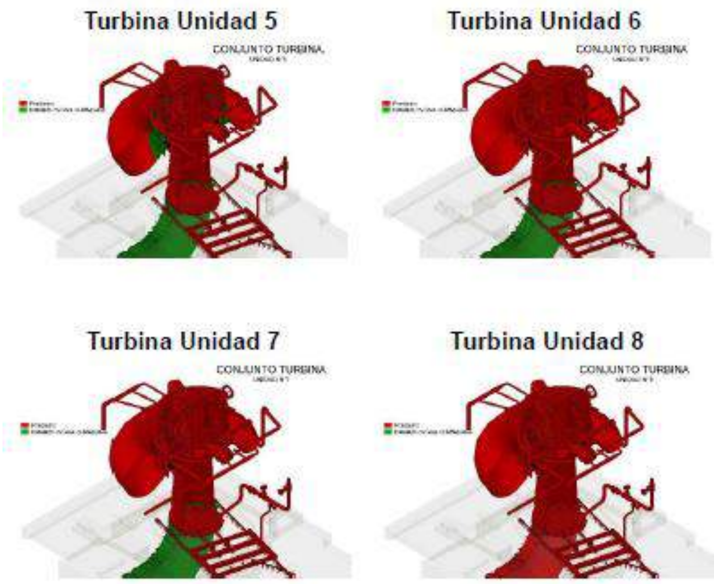



*Figure 25: Turbine equipment available in the warehouse*

Both the control gates of draft tubes 1 to 4 and the guides of 5 and 6 were lost in the contingency; some parts of gates were found destroyed inside the tailrace tunnels and the entire hydraulic circuit and its control system disappeared (see fig. 26).

*Figure 26: Slot for unit 5 draft tube gate in the south shaft chamber: guides are lost*

### 3.2 Summary of the assessment process

The decision of total replacement of Unit 3 and Unit 4, including first and second phase concrete and embedded parts basically completed the phase of the assessment of electromechanical equipment and allowed the placement of all orders necessary to reconstitute the entire electromechanical supply of Ituango. The following table summarizes the orders.

| Contract | Scope of works | Contractor | Value |
|---|---|---|---|
| CT-2012-000039 | Supply affected parts of Turbines, Generators and embedded parts of units 1 to 7<br>Installation services for units 1 to 4 | GE Energías Renovaveis Ltda | USD 84.018.422,87 |
| CT-2014-000507 | Supply and installation of 8 penstocks<br>Steel lining for environmental water release shaft | ATB Riva Calzoni Spa | USD 52.795.890 (supply)<br>COP 111.555.549.000 (installation) |
| CT-2013-00168 | Replacement of nineteen (19) Power transformers and their associated equipment | Siemens Transformer Guanzhou | USD 17.031.583 |
| CT-2015-000748 | Replacement of ten (10) 500 kV power cables and their associated equipment | Suedkabel GMBH | USD 2.820.362,60 |
| CT-2019-001291 | Supply of 2 x 300 tons overhead cranes | Industrias Electromecanicas GH | USD 2.555.728 |
| CT-2016-00085 | Supply of Electrical auxiliary services and Control System for the first 4 units | Siemens Colombia | USD 3.980.147 |
| CT-2017-000203 | Supply of cooling and drainage systems | Electrohidráulica S.A. | USD 1.576.000 |
| CT-2017-000204 | Replacement of the firefighting systems for the first 4 units | Tecnofuego S.A | USD 1.234.000 |
| CT-2017-000205 | Replacement of the Air conditioning system for the first 4 units | CSL Larco | USD 3.916.000 |
| New Contract | Power cable, control cables and cable trays for the first 4 units | to be defined | USD 900.000 |
| New Contract | Inclined Lift to replace electrical equipment, festoon cable and metal structures | Alimak | USD 579.000 |

### 3.3 Update on 500 kV GIS switchyard

The 500 kV switchyard is completed. Several HV power cables and most of the power and control cables, coming from the power plant, will have to be reinstalled. The cable gallery and its connections with the 500 kV GIS switchyard are in good conditions. Stabilization works were carried out in the slope above the switchyard area (fig. 27).

*Figure 27: The stabilization works [switchyard on the bottom left corner]*

### 3.4 Hydromechanical equipment

#### 3.4.1 Power Intake Gates

Activities on the Intake gates and their operating systems are proceeding at low pace because they are not on the critical path. Priorities, in this area, are underground reinforcement and slope stabilization works. Activities are currently concentrated on intake gates 3 and 4, the only ones in "dry" condition because isolated from the reservoir by concrete plugs (Fig.28, left). All other gates are currently lowered to their close position, 1 and 2 with their lifting devises, 5,6,7 and 8 by cranes (Fig. 28, right). Moreover, activities are underway on the guides of intake gates 5 and 6 to remedy the minor deformations suffered by these guides at the time of flooding the powerhouse.

*Fig. 28- Intake gates: Left, lowering gate 3 in its pit using temporary crane. Right: Inspecting guides of gates 5 and 6*

The following table summarizes the IAP's remarks on the Intake gates.

| Hydro Mechanical Equipment | Progress of installation and testing | Remarks |
|---|---|---|
| ***Intake Gates***<br>Height Sliding Gates, 5.03 x 6.87 m, with stoplogs<br>Operation: oleo dynamic servomotors. | The area is now accessible. A physical protection was installed above pit and control box of Unit 1 to 4. | Gates close under balanced pressure conditions and, in emergency, under the maximum hydraulic head and the rated flow of the Unit. However, it was demonstrated their capability to close under flow higher than the rated one. |

### 3.4.2 Steel lining to vertical shafts

The original design foresaw steel lining only on in the horizontal section between the lower elbow and the spiral case of the units. Given the large cavity in the area of pressure shafts 1 and 2, it ought to be assumed that the rock mass had lost its capacity to collaborate with the lining in withstanding internal pressures. The adoption of a self-standing, ductile, steel lining was recommended by the IAP. EPM acted rapidly, to avoid schedule delays in commissioning the first and signed the corresponding contract in 2019. Fig. 29 shows: (left) construction of the warehouse for manufacturing the penstock segments, and (right) the cable lift being lowered in the area of shafts 1 and 2.

*Figure 29 - Left: penstocks assembling area. Right: shafts 1 and 2, steel lining installation*

### 3.4.3 Gates of the GAD

The two GAD vertical sliding gates have successfully been lowered. A by-pass pipeline has been installed to alleviate the reservoir pressure on the gates, to increase safety when the permanent plugging to GAD and DT2 will be built. The temporary by-pass is routed through the IDG (see fig. 30).

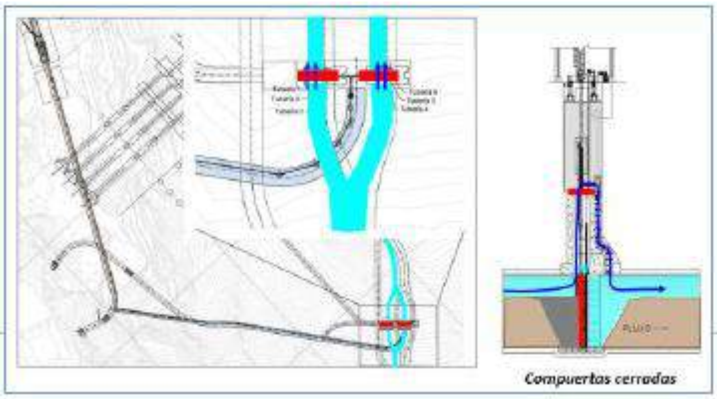



*Figure 30: GAD gates in their final position with temporary by-pass system*

EPM did not report any O&M problems for the equipment already installed and operated. After successful plugging of the GAD, the gate control chamber will be abandoned (fig. 31).

*Figure 31: Removal of the crane from the GAD control chamber*

### 3.4.4 Spillway and IDG gates

The following table summarizes the IAP's brief remarks on the Spillway's and IDG's gates.

| Hydro Mechanical Equipment | Progress of installation and testing | Remarks |
| --- | --- | --- |
| ***Spillway Gates***<br>Four Radial Gates (two with flap for debris) 15 m x 19,50 m<br>Cumulated discharge capacity: 22.600 $m^3/s$ (PMF)<br>Operation: oleodynamic servomotors, single control and oleodynamic stations for each gate + common control | Already in operation, testing and common control completed. | The position of the diesel generator building. In case of earthquake, rocks may fall from the slope and hit the building. Risk assessment is recommended. Statistics show that reliability of diesel generators in case of exceptional events is lower than expected. |
| ***Gates to intermediate Discharge Gallery***<br>Two Radial Gates + two Emergency Sliding Gates<br>Size: 3 m x 3.90 m (Radial Gates)<br>Setting capacity: 750 $m^3/s$ with both gates in operation for all reservoir elevation higher than 350 m a.s.l.<br>Operation: oleodynamic servomotors, single control and oleodynamic stations for each gate. | Already in operation conditions, testing and control completed. Steel lining installation duly completed. | None |

## 4 PROJECT COMPLETION- SCHEDULE AND COST IMPLICATIONS

### 4.1 Project's completion schedule

The scheme shown in fig. 32 provides a snapshot of the progress of the repair and recovery works in the powerhouse cavern complex. The following can be observed:

- The transformer hall is fully recovered (green colour).
- Most of the waterways and underground structures associated with units 1 and 2 has been repaired/ recovered (green) or in the process of being stabilized (yellow).
- Recovery works pertaining to units 3 and 4 are slightly behind 1 & 2, because the draft tube areas have not yet been inspected (violet).
- The waterways of units 5 to 8 have not yet been inspected and repairs are underway in the underground structure of the South part of the plant.
- Treatment of the pressure shafts to units 5 to 8 is under definition.

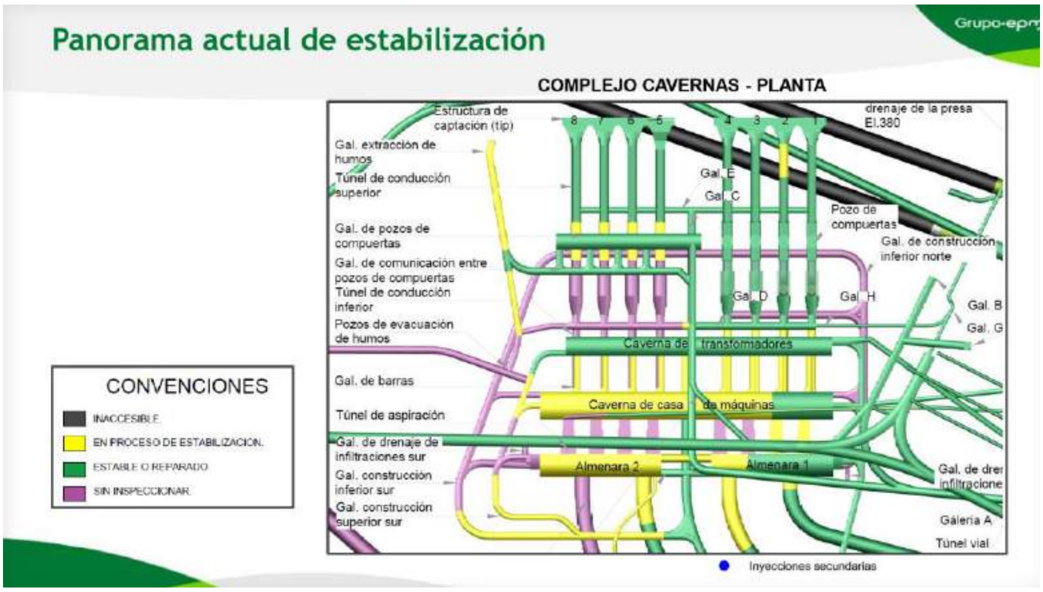



*Fig. 32: Recovery of underground works, progress overview at April 2020*

The IAP concurs with the methods being used for the recovery of the underground works pertaining to the North part of the plant (units 1 to 4). Achieving commercial operation is commented in the following section.

The assessment relative to the South part, units 5 to 8, is more challenging. The design of the pressure shafts recovery is currently under definition.

### 4.2 Achieving Commercial operation

EPM's March 30, 2020 schedule shows the following milestones:

- Commercial Operation Date of Unit 1: December 2021
- Commercial Operation Date of Unit 2: April 2022
- Commercial Operation Date of Unit 3: July 2022
- Commercial Operation Date of Unit 4: October 2022

Erection, commissioning and testing of Unit 1 may take approximately 9 months and this would leave enough time for EPM to proceed with first and second phase concrete. Timing is reasonable for an experienced contractor; the decision to totally remove all concrete works adds to the workload but facilitates decisions: a situation that experienced contractors always favour. In addition to that, due to the unprecedented rehabilitation works undertaken, EPM has been forced to develop a massive and efficient logistics that allows to operate on several fronts, in parallel, and to concentrate activities in one area if needed.

Few other considerations apply:

- Having GE Brazil directly involved in the erection of the first 4 units is a plus for the schedule.
- Enough long-term delivery equipment is present in the warehouses to guarantee the commercial operation of the first unit.
- Procurement schedule does not raise major concerns; slowdown of economy worldwide and few new orders play to Ituango's advantage.
- The only uncertain task is the completion of the complex activities associated with the intake works to units 2,3 and 4.

With the marginal reserve of the last point, the IAP considers feasible the current schedule to commercial operation.

### 4.3 Cost implications of the completion schedule

The IAP was asked to assess previous cost estimates, which did in its first report of October 2018. After that, due to the ongoing investigations and associated engineering work, insufficient elements were available to update that estimate. Progress achieved to date has allowed EPM to prepare a cost update for the completion of Ituango HPP as per April 2020. Data are shown in fig. 33; the last column converts COPs in million US$.

**PROYECTO ITUANGO**
**COSTO PPTO 2020**
**Millones COP Corrientes**

| CONCEPTO | TOTAL | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | ESTIM. 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | TOTAL (MUS$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 Ingeniería y administración | 1,829,450 | 123,316 | 79,265 | 161,068 | 107,060 | 126,833 | 144,230 | 183,385 | 205,362 | 234,044 | 238,069 | 80,683 | 59,014 | 47,830 | 39,299 | 476 |
| 1.1 Estudios y diseños | 53,963 | 53,903 | 36 | 26 | -2 | 0 | 0 | 0 | | 0 | 0 | 0 | 0 | 0 | 0 | 14 |
| 1.2 Interventoria | 487,397 | 12,251 | 19,690 | 29,481 | 30,936 | 38,721 | 53,751 | 69,412 | 71,746 | 65,728 | 45,715 | 16,381 | 12,571 | 12,719 | 8,296 | 127 |
| 1.3 Asesoria | 334,954 | 13,891 | 12,442 | 18,271 | 32,820 | 31,391 | 27,564 | 31,106 | 36,296 | 66,277 | 57,988 | 3,150 | 2,517 | 879 | 363 | 87 |
| 1.4 Auditorias | 4,307 | 120 | 247 | 251 | 217 | 328 | 425 | 427 | 0 | 651 | 547 | 547 | 547 | 0 | 0 | 1 |
| 1.5 Polizas | 112,893 | 19,402 | 18,666 | 4,542 | 7,262 | 7,616 | 10,250 | 11,524 | 14,016 | 10,751 | 3,992 | 4,544 | 328 | 0 | 0 | 29 |
| 1.6 Administración | 835,936 | 23,748 | 28,185 | 108,488 | 35,828 | 48,778 | 52,240 | 70,916 | 83,304 | 90,637 | 129,827 | 56,062 | 43,050 | 34,233 | 30,640 | 217 |
| 2 Costos directos | 10,147,927 | 156,589 | 356,655 | 594,598 | 945,645 | 1,148,584 | 1,179,445 | 1,533,293 | 1,171,658 | 825,421 | 1,010,262 | 788,515 | 291,369 | 114,597 | 31,294 | 2,639 |
| 2.1 Infraestructura | 1,868,382 | 146,481 | 272,358 | 299,855 | 260,155 | 319,160 | 170,878 | 194,670 | 69,916 | 53,817 | 37,549 | 30,139 | 13,402 | 0 | 0 | 486 |
| 2.2 Obras principales | 5,370,606 | 390 | 67,982 | 253,359 | 400,159 | 460,358 | 721,003 | 900,963 | 840,645 | 538,598 | 602,866 | 353,198 | 143,043 | 82,630 | 5,413 | 1,396 |
| 2.3 Equipos | 1,780,283 | 0 | 0 | 0 | 183,520 | 193,177 | 207,606 | 290,442 | 133,156 | 117,919 | 237,265 | 311,570 | 92,747 | 7,991 | 4,891 | 463 |
| 2.4 Gestión ambiental y social | 1,062,209 | 9,717 | 16,316 | 41,385 | 101,811 | 175,889 | 79,959 | 89,569 | 125,426 | 113,580 | 127,808 | 93,608 | 42,177 | 23,976 | 20,990 | 276 |
| 2.5 Conexión al STN | 66,446 | 0 | 0 | 0 | 0 | 0 | 0 | 57,649 | 2,516 | 1,507 | 4,774 | 0 | 0 | 0 | 0 | 17 |
| 3 Tierras y servidumbres | 91,320 | 7,543 | 4,588 | 7,547 | 8,674 | 4,899 | 6,717 | 21,471 | 15,516 | 8,094 | 6,271 | 0 | 0 | 0 | 0 | 24 |
| TOTAL INVERSIÓN | 12,068,696 | 287,448 | 440,509 | 763,203 | 1,061,379 | 1,280,317 | 1,330,392 | 1,738,149 | 1,392,535 | 1,067,559 | 1,254,602 | 869,198 | 350,383 | 162,427 | 70,593 | 3,138 |
| Gastos preoperativos | 393,809 | 6,471 | 6,882 | 9,650 | 25,639 | 25,342 | 29,402 | 21,059 | 165,465 | 76,989 | 13,163 | 9,065 | 4,682 | 0 | 0 | 102 |
| Gastos financieros | 2,479,576 | 0 | 0 | 40,366 | 64,033 | 139,280 | 233,368 | 285,302 | 335,465 | 397,635 | 388,602 | 376,437 | 112,692 | 73,540 | 32,857 | 645 |
| TOTAL CON GASTOS PREOPERATIVOS Y FINANCIEROS | 14,942,082 | 293,919 | 447,391 | 813,220 | 1,151,051 | 1,444,939 | 1,593,163 | 2,044,510 | 1,893,465 | 1,542,184 | 1,656,367 | 1,254,700 | 467,757 | 235,967 | 103,450 | 3,885 |
| IVA Descontable | 325,482 | 0 | 92 | 1 | 1,480 | 21,945 | 22,500 | 34,503 | 37,914 | 26,863 | 72,612 | 70,020 | 26,960 | 6,517 | 4,074 | 85 |
| TOTAL CON IVA DESCONTABLE | 15,267,564 | 293,919 | 447,483 | 813,221 | 1,152,532 | 1,466,884 | 1,615,663 | 2,079,013 | 1,931,379 | 1,569,047 | 1,728,979 | 1,324,719 | 494,717 | 242,485 | 107,524 | 3,970 |

*Fig 33: Completion costs- EPM's April 2020 estimate*

In line with the October 2018 assessment, indirect and financial costs (*gastos preoperativos y financieros*) are not included in the current review. Therefore, comparison between October 2018 and March 2020 cost estimates refers to direct costs only.

The costs shown in the first table of fig. 34 below are derived from EPM's April 2020 cost estimate and represent the sum of the indicated items from year 2020 to 2024.

EPM's Apr 2020

| Item | Cost (MUS$) |
|---|---|
| Infraestructura | 21 |
| Obras principals | 309 |
| Equipos | 170 |
| Gestion Ambiental y social | 80 |
| Conexion a STN | 1 |
| Tierras y servidumbres | 2 |
| Total directos | 583 |

EPM' Sep 2018

| DETALLE INVERSIONES CONTINGENCIA | Col Pesos | USD |
|---|---|---|
| 1. Obra civil | 369,000.00 | 123 |
| 2. Equipos (recuperación y reemplazos) | 332,750.00 | 111 |
| 3. Taponamiento túnel derecho y SAD | 100,000.00 | 33 |
| 4. Pantalla impermeable en la presa | 150,000.00 | 50 |
| 5. Desembalse | 300,000.00 | 100 |
| **TOTAL ESTIMADO EPM** | **1,251,750.00** | **417** |

IAP's Oct 2018

| ITEM | min | max |
|---|---|---|
| **Civil works** | | |
| Taponamiento tunel derecho y SAD | 30 | 40 |
| Pantalla impermeable en la presa | 50 | 50 |
| Extension of spillway slopes' treatment | 25 | 50 |
| Repairs and reinforcement to power house cavern | 30 | 50 |
| Reservoir landslide risk mitigation | 10 | 15 |
| Intermediate Discharge Gallery | 3 | 5 |
| Steel lining to penstock elbows | 10 | 15 |
| Middle level outlet (Desembalse) | 100 | 100 |
| **Subtotal Civil Works in USD Million** | **258** | **325** |
| **Equipment** | | |
| Generation Equipment | 80 | 100 |
| Balance of plant | 10 | 20 |
| Gates and valves | 5 | 10 |
| **Subtotal Equipment in USD Million** | **95** | **130** |
| | | |
| **TOTAL EQUIPMENT + CIVIL WORKS IN US MILLION** | **353** | **455** |

*Fig. 34: Cost estimates comparison*

The other two tables represent, respectively, the EPM September 2018 estimate and the IAP's assessment October 2018. In that opportunity, the IAP provided a cost range. It must be noted that the September 2018 estimate foresaw the realisation of a Mid-Level Outlet (*Desembalse*), which is not included in the April 2020 estimate.

The cost estimate of September 2018 was equal to 417 M$. In March 2020, after assessing the magnitude of the extensive repairs to the underground works, the estimate has escalated to 583 M$. In terms of civil works required for commissioning units 1 and 2, two sets of activities present the major uncertainties:

- The lower parts of the pressure shafts to units 1,2,3, 4 have not yet been inspected. They could need major repairs and become critical in the completion plan.
- Completing the Intermediate Discharge (essential for ANLA clearance) requires permanent plugging of TD2 and GAD, which entail complex activities, still subject to significant uncertainties.

More investigations and tests are required to define in detail the civil works required for commissioning units 5 to 8. The IAP considers premature to assess the relative cost implications, until investigations and design have reached a sufficient level of reliability.

The March estimate for cost associated with "Obras Principales", from 2020 to 2024, totals 309 M$ (equivalent). Allocating a contingency of 50 M$ (about 15% of 309) to face unforeseen requirements seems reasonable.

In conclusion, the current estimate of direct costs for the completion of the civil works can be assumed in the order of 633 M$, i.e. about 50% more than the Sep 2018 estimate (417 M$).

In terms of EM equipment and gates, comparison with the October 2018 estimate is not immediate, because the bulk of the additional costs are expected to be sustained by the insurance companies. Consequently, the cost increased only of 17.4 million US$ (66,818 million COP).

## 5 RESIDUAL RISK DURING OPERATION

### 5.1 Generation and Hydromechanical Equipment

As said above, all affected EM equipment, along with embedded parts, will be entirely replaced. Therefore, the level of risk during operation may be evaluated as if the flooding had not occurred.

In line with industry standards, some potential risk elements are evaluated and assessed in the following table.

| Equipment | Risk evaluation | Risk assessment |
|---|---|---|
| Spillway gates | Differential movement of the civil structure may cause serious consequences on the radial gates of the spillways, notably for gates of large dimensions. | **Negligible**: because of good rock foundations. |
| Intake gates system | The quality of completion and commissioning of the intake gates system was not uniform among the 8 intakes. The possibility of different behaviour of the intake gates could therefore be postulated. | **Low**: the experience learned, and the success achieved by EPM in closing intake gates 1 and 2, allow to consider this a Low risk. |
| Intake gates system | Differential movements of the civil structures to which the intake gates guides are fixed. | **Minimum**: good rock foundations, along with the success achieved by EPM in managing the intake gates. |
| Penstocks | Cracks or joint opening associated with differential movements. | **Minimum**: the use of steel lining has dramatically reduced the risk. Besides, the adoption of ductile steel in alternative to high-strength steel, increases the resilience to differential movement without cracking or limiting crack's propagation. |
| Turbine-generator units | Theoretically, the equipment could be affected by differential movement of the civil structures. | **Negligible**: given the quality of the rock mass, and the extent of the executed rehabilitation measures, differential movements can be positively ruled out. |

Despite what is often perceived, the margin for realigning a hydraulic unit whose civil works are subject to differential movements is relatively ample. While the precision of the mechanical regulations, at the time of unit's alignment, is a matter of microns, the margin for counteracting movements of the structure is in the order of several centimetres, enough to deal with any reasonable movement. A couple of such cases, in Africa plants, are known in the industry.

### 5.2 Turbines operation in "Speed-No Load" conditions

During the virtual mission, a discussion was held about the possibility of operating the turbine in "speed-no load" (SNL) conditions. That operation would allow, albeit for a limited time, to implement ecological flow releases when the plant is off-line, and reservoir is below spillway level.

The IAP observes that SNL represents a non-conventional use of the units, and the following observations are pertinent.

- All turbines are designed to remain in SNL operation for a relatively short time (minutes / tens of minutes), as a step in the synchronization process. Depending on design, some turbines may be operated as spinning reserve for longer period. This possibility should be verified with the manufactures.
- There is limited experience in operating units in "no load" conditions, at rotating speed higher than the synchronous one, for relatively long periods. While the possibility cannot be ruled out, it would require extreme care and should be supported by a dedicated study by the manufacturers. Frequencies of resonance of the shaft should be verified and actual prototype behaviour may be not entirely predictable in the model.

Based on the above, the IAP discourage the recourse to SNL operation. Different is the case of possible operation of the units below elevation 390 masl, which is discussed in section 5.5.

Should the interest on SNL return, the following considerations apply to the SNL practice.

- Maintaining the pressurized oil injection in the trust bearing pads even after the start-up of the unit increases safety in operation by ensuring the establishment of a thicker oil film above the pads. Oil injection is adopted at Ituango. This practice is not reported to have any collateral problem.
- When units, like the ones of Ituango, are designed with natural air injection below the runner, activated in selected area of the operation range, it is often possible to upgrade the natural injection to forced injection. The latter has the benefit to “regularize” the water flow water and consequently the operation and the vibration of the unit. Such benefit is paid by a slightly lower efficiency and with the additional consumption of air compressor pumps.

### 5.3 Reservoir Control during Project Operation

The IAP has discussed the subject of reservoir control, during Project’s operation, in all its reports, from August 2018 onwards. Having waterways of sufficient capacity to manage river inflows allows controlling reservoir levels for:

- Safety: the upper part of the reservoir must be lowered in emergency conditions (e.g. post-earthquake, or for internal erosion manifestations), even when discharge through the turbines cannot be relied on.
- Maintenance: to access the intake gate areas for extraordinary maintenance or repairs.

For the time being, the only control waterway is the surface spillway, which cannot be used to lower the reservoir below el. 401. When the turbines will be in operation, reservoir control will improve, and the more so when all the units will be available for generation.

At the same time, there may be situations, along the life of the Project, when turbine flow is interrupted (no demand, transmission line failure, post-earthquake, etc.). The availability of an independent waterway (Middle Level Outlet), of adequate hydraulic capacity, to achieve reservoir control would be a key element in the interest of the long-term safety of Ituango HPP.

If, God forbids, such contingency was to occur during operation, nobody will remember, and give weight to the challenges faced during construction.

The IAP understands the Designer’s legitimate concerns associated with the difficulties of realizing additional discharge capacity in a rock mass with locally disturbed areas and that already houses several tunnels. No question the endeavour would entail significant risks, but those risks should be compared with those associated with the inability of managing an emergency, during operation, for lack of adequate reservoir control.

To assist EPM in making a risk-informed decision, the IAP conducted a demonstrative PFMA workshop during the virtual visit.

### 5.4 The PFMA Workshop

The PFMA (Potential Failure Mode Analysis) session was conducted on May 21st. The proceedings are reported in Annex B, and conclusions can be summarized as follows.

- Integral is undertaking a comprehensive Risk Assessment of the Project, applying the PFMA technique to a large set of potential failure modes. Integral confirmed that the approach is, in principle, the same as the one used by the IAP and that the May 21st session provided useful insights for the next steps of the exercise that Integral is carrying over.
- The Probability of Failure (PF) obtained, for the two PFM analysed on May 21st, range from 5*10^-5 (maximum) to 3*10^-6 (minimum). It is desirable, for a project of the importance and hazard level of Ituango, to aim at the "ICOLD range" for PF, i.e. 10^-6 to 10^-5.
- Two key measures can achieve that result:
  - Operate the turbines at elevations below 390 masl, and
  - Adding a Mid-Level Outlet.
- The first measure seems feasible and is dealt with in the next paragraph.
- Adding an MLO to Ituango, albeit very challenging due to the presence of the reservoir, should not be forsaken because it would remarkably increase Project safety. In consideration of the difficulties involved, construction must be carefully planned and, if confirmed essential, built during the life of the Project.
- The decision should be Risk-Informed, i.e. the PFMA should be repeated, with more detailed probability estimates and the range of PF compared to that associated with the construction of an MLO. The IAP encourages EPM and Integral to undertake the exercise. The IAP will be pleased to review the relative report.

In conclusion, the PFMA workshop achieved the intended result of rising awareness on the paramount importance of reliable reservoir control during operation. The PFMA also allowed identifying important elements, such as the possibility of operating the turbines below 390 masl, which require serious follow-up.

### 5.5 The possibility of operating the units below el. 390 masl

The operating head of Ituango reservoir, as defined in its design, is nominally limited to 30 m range: between 420 and 390 masl (fig 35).

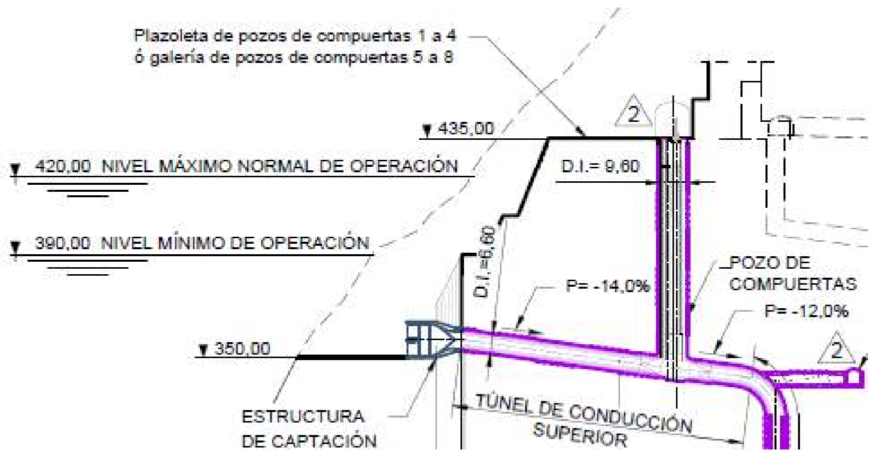


*Figure 35: Maximum normal, and minimum operating levels*

The design decision for that range was made long time ago and its reasons seem somehow be lost. Project layout and the reservoir geology do not appear be the reasons for such decision, nor the presence of floating debris may be considered the constraining factor.

The IAP feels that such range derived from the simulation of the reservoir operation in the scenario maximizing the output of the power house and that the same range was then requested to the turbine manufacturer who, in turn, limited the operating range to what requested by the client.

The possibility emerged, during the PFMA Workshop, as a big help to controlling reservoir levels under emergency conditions. The capability to lower the reservoir level below 390 masl may indeed become a critical measure to extent the reservoir management options, currently very limited, and consequently to increase Project' safety in operation. Hence, the matter needs to be seriously re-evaluated by EPM. Needless to say, consultation with the equipment suppliers should be sought.

In the following, the IAP elaborates on the electro-mechanical aspects of the head range modification. Under normal operation and exceptional operation (limited to four / eight hundreds of hours per year), the operating Net Head of Francis turbines is normally in the range of:

- Net Rated Head + 10% and
- Net Rated Head -25/30 %

In that range, efficiency drops but units are not affected or marginally affected.

Such range corresponds to a "Minimum Head / Maximum Head" ratio of approximately 65%.

Similar ranges would translate for Ituango in the possibility of lowering the reservoir to, say, el. 370 masl, or thereabout. This possibility would allow to control the reservoir level after an earthquake (safety objective). It could also facilitate interventions of extraordinary maintenance of the intake works (maintenance objective).

Restricting the minimum operation level to 390 masl for avoiding vortexes at the intakes appears an excessive design measure and should be re-assessed by the engineer. In similar emergency situations, established practices include:

- Constant supervision at the intakes, to spot incipient vortex formation, and
- Monitoring any strong noises from the spiral cases, caused by the expansion of the first air bubbles.

The following table summarizes the IAP understanding of Ituango head ranges (slightly dissimilar number were found in different documents).

| Head | Ituango Turbine Net Head value [m] | Ituango Turbine Net Head value [%] | Ratio | Values [ p.u.] |
|---|---|---|---|---|
| Max. | 207 | 104,9 % | Max. / Min | 1.25 |
| Normal | 197,3 | 100,0 % | | |
| Minimum | 166 | 84,1 % | Min / Max | 0.80 |

Fig. 36 shows Ituango's turbine "hill-chart". The "Continuous Operating area" appears the result of EPM's request for an area of very high efficiency rather than a physical limitation. The ratio Gross Maximum Operating Head / Gross Minimum Operating Head based on reservoir level is approximately 85% and the ratio Minimum Head / Maximum Head of the prototype as per Model Test is 80%. Both numbers are on the low side.

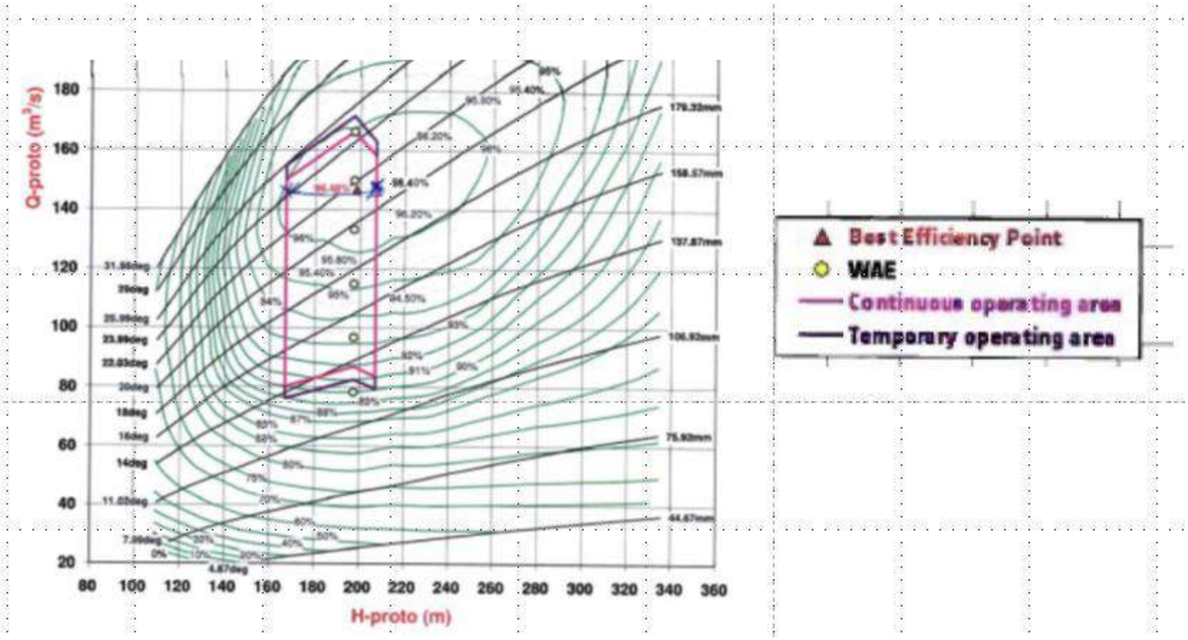



*Figure 36: Ituango Turbine Hill Chart*

Moreover, it should be noted that the operation of the turbine below its official minimum head would still fall in an area of high efficiency (above 90-91%), especially for high values of Q (the ones more interesting). That indicates respectable turbine performance.

The following table compares the Ituango's turbine with that of another turbine[2] having similar specific speed (nq).

| Turbine parameters | Unit | Ituango | Power Plant with turbine having similar nq |
|---|---|---|---|
| N rpm | rpm | 180 | 166,7 |
| Q | $m^3/s$ | 169 | 278 |
| H | m | 197.4 | 254 |
| nq | - | 44 | 45 |
| H min | m | 166.9 | 185 |
| H max | m | 207 | 320 |
| H max/H min | - | 1.24 | 1.73 |
| H rated / H min | | 1.18 | 1.32 |

References from other hydropower plants in South America (courtesy of KfW based on publicly available data):

- SOGAMOSO HEPP (Colombia; 3 x 273 MW = 820 MW – Colombia) D of Turbine = 4,5 m
  Hn = 145,5 m / Hmax = 155 / Hmin = 107 m ; Range = + 7% / - 27%
- GURI 2 HEPP (Venezuela 10 X 770 MW) D Turbine = 7 m
  Hn = 134, Hmin 108; Hmax = 144; Range = + 7% / - 20%

Finally, fig 37 shows examples of hill charts proposed by two different manufacturers for exactly the same turbine to be installed in different parts of the same power plant; those turbines are similar, in size, to Ituango's. It may be noted the wide range of operation and, not less important, the differences among manufacturers.

[2] Name of the project cannot be quoted for confidentiality reasons.

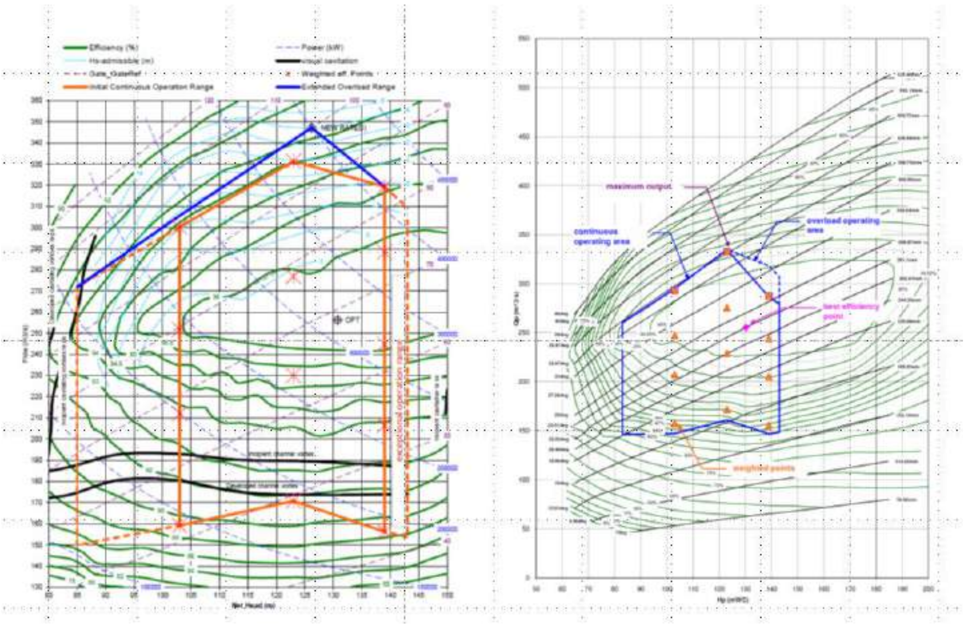



*Fig. 37: Hill charts proposed by two manufactures for the same turbine*

In conclusion:

- The possibility of operating Ituango’s turbines below el 390 masl appears technically feasible.
- Supplier’s opinion is essential, including his feedback on guarantees efficiencies.
- Analysis of the model test report including pressure pulsations and cavitation curves is also essential.
- The turbine physical model is reportedly still available and can be used to validate.

# 6 ANNEX A: LIST OF DOCUMENTS MADE AVAILABLE TO THE IAP

- 1Presentación Técnica Proyecto Hidroeléctrico Ituango mayo 2020, EPM;
- 20200516_Stilling basin, Integral;
- 20200518-_DAM, Integral;
- 20200518_NorthZone_Lower_Elbows, Integral;
- 20200518_Power_house_caverns, Integral;
- 20200518_SouthZone, Integral;
- 20200518_Superficial, Integral;
- 20200519 presentación asesores BID_Aseguradora,
- BID RISK PRESENTATION 20 Mayo 2020, EPM;
- DI_GAD_TDD-Presentation1, Mayo 2020, Integral;
- Environmental Flow, Mayo 2020, Integral;
- ITUANGO-Costo ppto 2020 y comparación costo ppto 2019, EPM;
- ITUANGO COSTO Marzo2020, EPM;
- Presentación BID 3 de abril Extract 3. PROGRAMA DE PUESTA EN OPERACIÓN, abril 2020, EPM;
- Seguimiento Avance Megaproyectos Ituango_Dic_2019, EPM.

# 7 ANNEX B: POTENTIAL FAILURE MODE WORKSHOP on May 21st

## 7.1 Rationale

The availability of hydraulic works to lower the level of the reservoir, under exceptional circumstances when turbine operation cannot be relied on, is fundamental for the safe performance of the project over the long term.

The subject of long-term reservoir control is too important and requires detailed examination, including risks assessment, definition of mitigation measures, and preparation of contingency plans. To this end, the IAP conducted a PFMA (Potential Failure Mode Analysis) workshop to analyse potential scenarios of project operation, or failure to operate, under different waterways configurations.

## 7.2 Objectives of the PFMA workshop

i) To assist EPM reaching a Risk-Informed decision on the most appropriate measures to ensure safe and reliable operation of Ituango HEP.

ii) To assist the transition between construction and operation, with particular reference to Project's Instrumentation & Monitoring, Operation & Maintenance, and Emergency Preparedness.

With reference to the second objective, the IAP understand that Integral has already conducted PFMA sessions considering a wide range of potential failure modes. Such sessions are scheduled to continue until Project's completion.
The session involved all key stakeholders, representatives of the EBIA, and POYRY were also present. The full list of participants is shown in Annex C.

## 7.3 Introduction to PFMA

For the benefit of those not familiar with the method, the IAP introduced the PFMA using a presentation in Spanish. The presentation is shown in Annex D.

### 7.4 PFMA process

Two PFM frameworks were analysed which are relevant to reservoir control during operation:

- SB: **Spillway blocked** by a massive landslide, and
- ED: **Emergency reservoir drawdown**, required after a strong earthquake and/ or evidence of progressing internal erosion.

The two PFMs are not exhaustive but are considered highly informative for Objective i).

The Event Tree method, implemented on XLS sheets, was used for the analysis. The method entails assigning probabilities to each postulated event/ status of the system. Probabilities can be assigned in one of four ways, or combination of them:

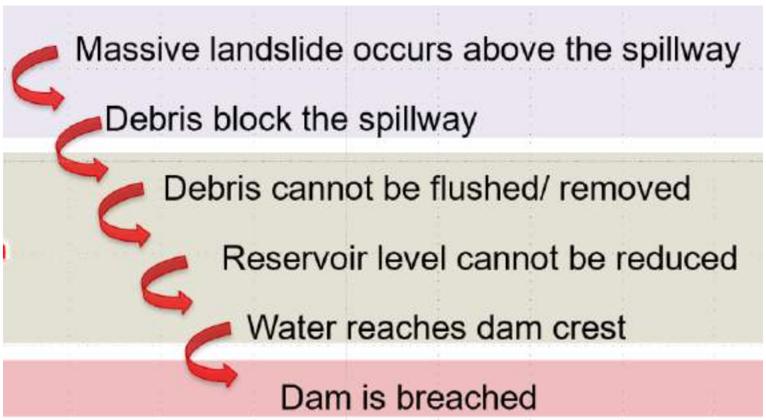
- Engineering models based on physical processes (e.g. flood frequency),
- Statistical estimates based on empirical data (e.g. erodibility of a certain soil type),
- Fault tree based on logical construction (e.g. equipment mis operation),
- Judgement (e.g. expert elicitation process).

In all cases, judgement is inevitably involved. It is therefore very important that a consistent reference is used to associate a probability value to subjective descriptors. The following reference was used in the workshop.

| Descriptor | Associated Probability |
|---|---|
| Virtually Certain | 0.999 |
| Very Likely | 0.99 |
| Likely | 0.9 |
| Neutral | 0.5 |
| Unlikely | 0.1 |
| Very Unlikely | 0.01 |
| Virtually Impossible | 0.001* |

#### 7.4.1 PFM SB: Spillway blocked by landslide

Postulated mechanism of failure:




The event tree is shown in Annex E. Five steps compose the event tree:

- Initiation,
- Emergency Response

- Intervention
- Progression
- Breach

Each node of the event tree has a dual outcome:

- Process stops and failure cannot occur, or
- Process continues.

The sum of the respective probabilities must equal 1 (mutually exclusive events).

Multiplication of the probabilities along the tree's branches that reach "breach" give the probability of failure.

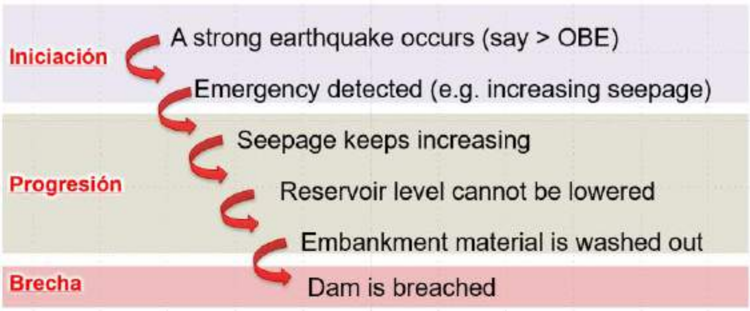
The upper branch of the event tree counts only on turbine discharge for controlling the reservoir. Should turbine not be available during the emergency it would be impossible to maintain the reservoir below the spillway level, and the process could continue to attain dam breach. The overall probability of failure would be 2*10-5, i.e. 2:100,000, a very low but not negligible value according the following categorization:

| Category | Probability range (per year) |
|---|---|
| Neglegible | Indistinguishable from 0 |
| Very Low | < 10-4, except 0 |
| Low | 10-3 to 10-4 |
| Medium | 10-2 to 10-3 |
| High | 10-1 to 10-2 |
| Very High | > 10-1, not 1 |
| Certain | 1 |

The lower branch postulates the availability of a Mid Level Outlet (MLO). Should turbines be unavailable during the emergency, the MLO could control the reservoir and failure averted. Should no MLO be available, the process could continue to attain dam breach. The overall probability of failure would be 5*10-5, i.e. 5:100,000, slightly higher than the previous one.

### 7.4.2 PFM ED: Emergency reservoir drawdown

During operation, emergency reservoir drawdown could be required following a strong earthquake and/ or evidence of severe internal erosion. Postulated mechanism of failure:



The event tree is shown in Annex F

As in the previous case (PFM SB), the upper branch of the event tree counts only on turbine discharge for controlling the reservoir. Should turbine not be available during the emergency it would be impossible to lower the reservoir to a safe level, and the process could go on attaining dam breach. The overall probability of failure would be 4*10-5, i.e. 4:100,000, a very low but not negligible value. The lower branch postulates the availability of an MLO. Should turbines be unavailable during the emergency, the MLO could control the reservoir and failure averted. Should no MLO be available, the process could go on attaining dam breach. The overall probability of failure would be 3*10-6, i.e. 3:1000,000, lower than the previous one.

### 7.5 Stocktaking

The IAP learned that Integral is undertaking a comprehensive Risk Assessment of the Project, applying the PFMA technique to a large set of potential failure modes. Integral confirmed that the approach is, in principle, the same as the one used by the IAP and that the May 21st session provided useful insights for the next steps of the exercise Integral is carrying over.

The PF obtained, for the two PFM analysed on May 21st, range from 5*10^-5 (maximum) to 3*10^-6 (minimum). To put such values in perspective, it should be noted that the PF of modern dams is generally considered to be around 10^-5[3], and that the ICOLD "vision" and commitment is to further reduce that PF to 10^-6. Figure 38 puts the above values in perspective (indicative ranges for small dams[4] and tailings facilities[5] are shown for comparison). *If one reverses the figure, i.e. Safety Margin = 1/ PF, the picture may become more familiar for those not acquainted with probabilities.*

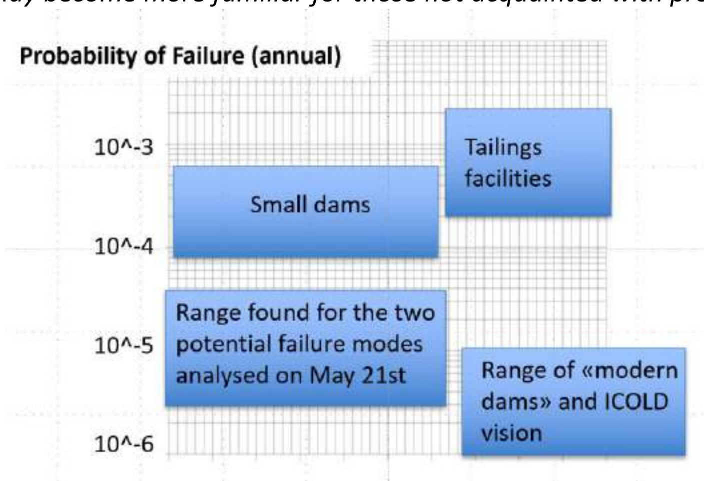



*Fig. 38: Probabilities of failure put in context*

It is desirable, for a project of the importance and hazard level such as Ituango, to aim at the "ICOLD range". Two key measures can achieve that result:

- Operate the turbines at elevations below 390 masl, and
- Adding a Mid-Level Outlet.

The first measure seems feasible and is discussed in section 5.5 of the present report.

[3] ICOLD (2017) "Dam Safety Management", Bulletin 154.
[4] ICOLD (2016) "Small Dams Design, Surveillance and Rehabilitation", Bulletin 157.
[5] ICOLD (2018) "Tailings Dam Design, Technology Update", Bulletin 181.

Adding a MLO to Ituango, albeit very challenging due to the presence of the reservoir, should not be forsaken because its reservoir control function would remarkably increase Project safety. In consideration of the difficulties involved, construction must be carefully planned and, if confirmed essential, built during the life of the Project.

The decision should be Risk-Informed, i.e. the PFMA should be repeated, with more detailed probability estimates and the range of PF compared to that associated with the construction of an MLO. The IAP encourages EPM and Integral to undertake the exercise. The IAP will be pleased to review the relative report.

In conclusion, the PFMA workshop achieved the intended result of rising awareness on the paramount importance of reliable reservoir control during operation. The PFMA also allowed identifying important elements, such as the possibility of operating the turbines below 390 masl, which requires serious follow-up.

# 8 ANNEX C: PFMA Workshop- List of participants

| NOMBRE | ENTIDAD | CARGO |
|---|---|---|
| Bayardo Materón | Board de Asesores | Especialista en Presas |
| Gabriel Fernández | Board de Asesores | Especialista en Geotecnia |
| Adriana Cubides Cruz | EPM | Profesional Gestión Proyectos e Ingeniería |
| Alejandro Giraldo | EPM | Profesional Gestión Proyectos e Ingeniería |
| Angela Vergara Jaller | EPM | VP Riesgos |
| Bladimir Suarez | EPM | Jefe Unidad Operaciones Ituango |
| Gloria Tobón | EPM | Profesional Gestión Proyectos e Ingeniería |
| Jesús María Arango | EPM | Profesional Experto. |
| Jorge Tabares Ángel | EPM | Vicepresidente de Finanzas e Inversiones |
| José Alberto Eusse | EPM | Profesional Ambiental y Social |
| Juan Carlos Gallego | EPM | Profesional Gestión Proyectos e Ingeniería |
| Juan Carlos Gutiérrez | EPM | Profesional Experto |
| Juan Carlos Palacios | EPM | Profesional Finanzas y Gestión del Riesgo |
| Juan Carlos Sampedro | EPM | Director de Gestión de Capitales |
| Julián Montoya | EPM | Profesional Gestión Proyectos e Ingeniería |
| Leonardo Henao | EPM | Profesional Ambiental y Social |
| Luis Alberto Sierra | EPM | Profesional Experto |
| Marcela Grajales | EPM | Profesional Financiero Dirección Gestión de Capitales |
| Mary Sol Londoño Perez | EPM | Profesional Financiero |
| Mauricio Correa | EPM | Jefe Unidad Hidrometría y Calidad Generación Energía |
| Michel Aljure | EPM | Profesional Gestión Proyectos e Ingeniería |
| Nestor Daniel Jurado | EPM | Profesional Gestión Proyectos e Ingeniería |
| Oscar Sierra | EPM | Profesional Gestión Proyectos e Ingeniería |
| Otoniel Corrales | EPM | Profesional Experto |
| Robinson Miranda | EPM | Director Ambiental, Social y Sostenibilidad Proyecto Ituango |
| Rodrigo Mazo | EPM | Profesional Financiero |
| Stefano Di Ubaldo C. | EPM | Director Desarrollo Proyecto Ituango |
| Tatiana Isaza | EPM | Directora Seguros Corporativos |
| William Giraldo | EPM | Vicepresidente Proyectos Generación Energía |
| Wilson Javier Sánchez | EPM | Profesional Finanzas y Gestión del Riesgo |
| Alessandro Palmieri | IAP | Especialista en Presas y Obras Hidráulicas |
| Federico Ciampitti | IAP | Especialista Electromecánico |
| Paulo Marinos | IAP | Especialista en Geotecnia |
| Alexi Adriana Duque | Integral | Residente de Instrumentación |
| Fabio Villegas | Integral | Asesor |
| Gabriel Lacouture | Integral | Líder Especialista en Hidrología e Hidráulica |
| José Ignacio Hernández | Integral | Director Técnico de Proyectos |
| Juan Bernardo Salazar | Integral | Ingeniero Civil Analista de Riesgos |
| Juan Camilo Arango | Integral | Ingeniero Mecánico |
| Juan David Herrera | Integral | Residente de Geotecnia |
| Juan Luis Cadavid | Integral | Director Genera |
| María Cecilia Sierra | Integral | Especialista en Geociencias |
| Ricardo Germanetti | Integral | Líder Técnico Área de Estructuras |
| Santiago Rivera | Integral | Ingeniero |
| Jacobo Ojeda | Interventoría | Profesional |
| José Iván Bohórquez | Interventoría | Jefe de Túneles y Conducciones |
| Tito Martínez | Interventoría | Director Técnico |
| Oscar González | KfW | Ingeniero Mecánico – Experto Sénior en Energía |
| Matías Egaña | POYRY | Ingeniero Geólogo |
| Patrick Furrer | POYRY | Gerente de Proyecto |
| Santiago Castro | POYRY | Geotécnico |
| Winfred Riemer | POYRY | Experto en Presas |

# 9 ANNEX D: Modo de Falla Potencial- Basico

IDB | Invest

**Ituango HPP**

Independent Advisory Panel to IDB Invest

**Taller de los Modos de Fallo Potenciales**

**Modo de Fallo Potencial Análisis – Básico**

Alessandro Palmieri

Mayo 2020

## Modos de Fallo Potenciales en Presas

**Definición de Fallo:**

- La liberación incontrolada de agua del embalse a través de la rotura de la presa o una estructura accesoria (aliviadero, toma, etc.)

Teton Dam Failure, 1976

- La descarga incontrolada por fallo del equipamiento o una operación no planificada

Folsom Dam Spillway Gate Failure, 1995

## Modos de Fallo Potenciales en Presas

**Un Modo de Fallo Potencial (PFM) son una serie de eventos que pueden originar el fallo de la presa.**

- El riesgo de fallo de la presa se puede reducir al comprender los modos de fallo potenciales.
- Esto implica comprender cómo y por qué fallan las presas:
  - Comprender cómo se comportan normalmente nuestras presas.
  - Aprender a identificar las primeras señales de que algo va mal.
  - Comprender los peligros y riesgos existentes en la presa.
  - Comprender el impacto potencial del fallo en la comunidad de aguas abajo.
  - Estar preparado para el comportamiento inesperado del fallo.
- FERC (USA) Guía de Ingeniería para la Evaluación de Proyectos Hidroeléctricos. Capítulo 14: *PROGRAMA DE MONITOREO DEL FUNCIONAMIENTO DE LA SEGURIDAD DE LA PRESA*

## Modos de Fallo Potenciales en Presas

**Cómo se producen los Modos de Fallo Potenciales**

- **Iniciación**: PFMs se inician por un peligro o un evento.
- **Progresión**: Para que suceda el fallo tienen que darse una cadena de eventos.
- **Intervención/Brecha**: La progresión se detiene por la intervención humana o porque casi se llega a la rotura de la presa.

| Iniciación | Progresión | Intervención / Brecha |
|---|---|---|
| • La condición, peligro o evento que produce el Modo de fallo (Ej. incremento del nivel de embalse debido a una avenida; fuerte sacudida sísmica; mal funcionamiento de la compuerta del aliviadero; filtraciones a través de la presa de tierra; etc.) | • Progresión paso a paso del fallo. (Ej. La cadena de eventos que tienen que ocurrir para que se produzca el fallo). Se debe señalar la localización, donde es más probable que suceda el fallo. | • Los caminos de la intervención humana que pueden usarse para evitar la progresión del PFM.<br>• La descripción de la brecha incluyendo la velocidad de ocurrencia del suceso. |

## Modos de Fallo Potenciales en Presas

Ejemplo #1. Modo de Fallo Potencial. Sobre-vertido de la presa

| | |
|---|---|
| Iniciación | Crece el nivel del embalse |
| | Se bloquea el vertido del aliviadero |
| Progresión | Decrece la capacidad del aliviadero |
| | Se produce sobrevertido de la presa |
| | Produce la erosion del terraplén de tierra |
| Brecha | Se produce una brecha en la presa |

## Modos de Fallo Potenciales en Presas

Ejemplo #2. Modo de Fallo Potencial. Erosión Interna

| | |
|---|---|
| Iniciación | Defecto en el terraplén de la presa |
| | El gradiente de filtraciones erosiona partículas finas |
| Progresión | El Filtro no es compatible con el Núcleo |
| | Los finos migran a través de la presa. |
| | El defecto se erosiona y hace más grande |
| Brecha | Se produce una brecha en la presa |

## Modos de Fallo Potenciales en Presas

- Determina cuál PFMs tiene la mayor probabilidad de ocurrir en tu presa y cuales son los indicadores claves.
- Permite al propietario de la presa tomar acciones tempranas para prevenir el desarrollo del PFMs.


¿Dónde puedes identificar el PFM e intervenir?

## Modos de Fallo Potenciales en Presas

**El Proceso PFMA**

| Entradas | | Salidas |
|---|---|---|
| - Datos existentes de la presa, planos, informes, información, análisis de ingeniería, registros de construcción (si están disponibles), etc.<br>- Información de primera mano del personal de campo y operativo<br>- Inspección del emplazamiento | EVALUACIÓN DE LOS MODOS DE FALLO POTENCIALES | - Identificación de los Modos de Fallo Potenciales creíbles.<br>- Causas de los Modos de Fallo y pasos para que sucedan.<br>- Medidas de Mitigación.<br>- Instrumentación, vigilancia y auscultación. |

Modos de Fallo Potenciales en Presas

## El Proceso PFMA

| | |
|---|---|
| Paso 1 | • Nombrar participantes en la evaluación del Modo de Fallo Potencial |
| Paso 2 | • Recopilar datos e información relevantes para la presa |
| Paso 3 | • Leer y revisar información de antecedentes |
| Paso 4 | • Visitar la presa |
| Paso 5 | • Realizar un taller de PFMA |
| Paso 6 | • Documentar los resultados del taller de PFMA |

Modos de Fallo Potenciales en Presas

– Determine las cargas que podrían iniciar los Modos de Fallo Potenciales, incluidos los de peligros naturales

| | |
|---|---|
| Estático | • Condiciones de operación normal (Ej. Filtraciones a través del cuerpo de presa con nivel de operación de embalse normal). |
| Avenidas | • Precipitaciones importantes causan avenidas y ascensos del nivel de embalse (Ej. Sobrevertido de corona) |
| Sismo | • Cargas dinámicas causadas por un sismo (Ej. inestabilidad de taludes por sismo). |
| Operacional | • Errores en la operación /disfunción que pone en peligro la presa (Ej. Fallo de apertura de compuertas de aliviadero). |
| Otros | • Otras cargas relevantes en el emplazamiento (Ej, Deslizamientos, oleaje inducido por viento que produce sobrevertido). |

Modos de Fallo Potenciales en Presas

## Paso 5. Proceso del Taller PFMA

a) Introducción al Taller

b) Desarrollo y descripción de los Modos de Fallo Potenciales

c) Identificación de Factores Favorables y Adversos al MF

d) Detección de Modos de Fallo Potenciales

e) Considerar intervención

f) Documentación de los hallazgos

g) Planificación de las Medidas de Reducción

Modos de Fallo Potenciales en Presas

## Detección de Potenciales Modos de Fallo

- US Bureau of Reclamation (USBR) categories:

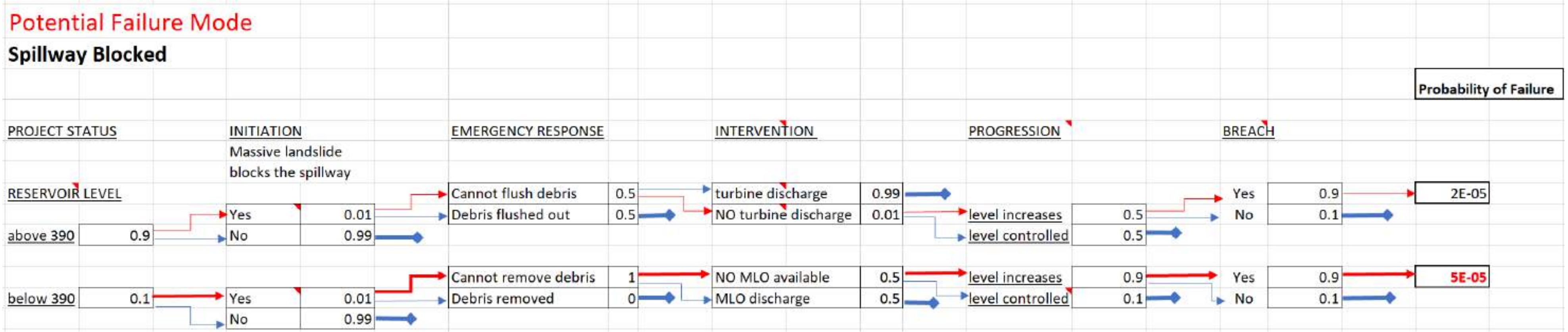
| Categoría | Descripción |
|---|---|
| Categoría I<br>Altamente creíble | **Altamente Creíble**<br>Estos posibles modos de fallo se han iniciado y están en progreso, o se espera que progresen en condiciones normales de operación o carga de diseño. Se pueden requerir medidas urgentes de emergencia, vigilancia o medidas de mitigación si la situación parece ser peligrosa en términos de probabilidad de fallo y las consecuencias resultantes del fallo. |
| Category II<br>Creible | **Creible**<br>Se considera que estos modos son significativos, pero no requieren medidas inmediatas para mitigarlos. Tenga en cuenta que aunque estos modos de falla potenciales se consideran menos significativos que la Categoría I, se describen con la misma cantidad de detalles. La razón de la menor importancia se anota y resume en el informe o notas de la documentación. |
| Category III<br>Insuficiente información | **Se necesita más información o require un análisis**<br>Para clasificar estos modos de fallo potenciales se requiere más información para permitir un juicio seguro. Se requieren más acciones de investigación o análisis para comprender estos modos de fallo. Debido a que se requiere una acción antes de la resolución, también se puede resaltar la necesidad de esta acción. |
| Category IV<br>No creible | **Descartado**<br>Estos posibles modos de fallo pueden descartarse porque no existe una posibilidad física. Hay información disponible que elimina la preocupación que había generado el desarrollo del modo de fallo potencial, o el modo de fallo es tan remoto que se determina que su probabilidad no es creible. |

Modos de Fallo Potenciales en Presas

## Taller PFMA - Resultados clave

- Definir relaciones funcionales entre modos de fallo potenciales y datos de monitoreo / instrumentación.
- Afina los tipos y ubicación de la instrumentación.
- Evaluar los niveles de embalse seguros.
- Establecer una línea de base de seguridad para la próxima evaluación de PFMA.
- Términos de referencia para Planes de seguridad de presas (instrumentación; O&M; preparación para emergencias / Matriz de nivel de respuesta).
- Plan de acción para mejorar la seguridad de la presa.

## ANNEX E: PFM SB: Spillway blocked by landslide




## ANNEX F: PFM ED: Emergency reservoir drawdown