ITUANGO HYDROELECTRIC POWER PLANT
COLLAPSE OF THE AUXILIARY DIVERSION TUNNEL
CONSTRUCTION ALL RISK POLICY No. 2901211000362
ROOT CAUSE ANALYSIS

REPORT OF

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Subject Matter: This root cause report pertains to the Ituango Hydroelectric Power Plant, Antioquia, Colombia, that was under construction when the Auxiliary Diversion Tunnel collapsed. The event was recorded as April 28 to 30, 2018.

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1. DISCLAIMER

1.1. This report has been prepared by Dr. Christopher Snee, Prof. Luiz Guilherme de Mello, Mr. Bernard Murphy, and Dr. Rafael Prieto, jointly referred to as the technical experts to the Adjuster, or the Experts. This work is entirely of the Experts unless identified otherwise and was developed from information provided and observations made on the site visit dates. The request for information (**RFI**) and the status of responses to the RFI are included in Appendix A.1. Citations are referenced as provided. The Experts make no representation or warranty concerning the accuracy or completeness of information provided. The Experts reserve the right to amend any of the content in this report if further information is provided or comes to light that, in the opinion of the Experts has a material effect on the investigation, analysis and conclusions.

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2. EXECUTIVE SUMMARY

Background to the Ituango Hydroelectric Power Project

2.1. The Ituango Hydroelectric Power Project (the **Plant**) is about 170 kilometers from the city of Medellin in the north-west of Colombia at 75°3946"W ; 7°0722"N , on the Cauca River, in the Department of Antioquia. It is located about 8 km downstream of the Pescadero bridge, on the road to Ituango. The Cauca River is about 1,350 km long, with a basin of 37,800 km^2 and discharges into the Magdalena River, which flows to the Caribbean Sea to the north (Figure 1).

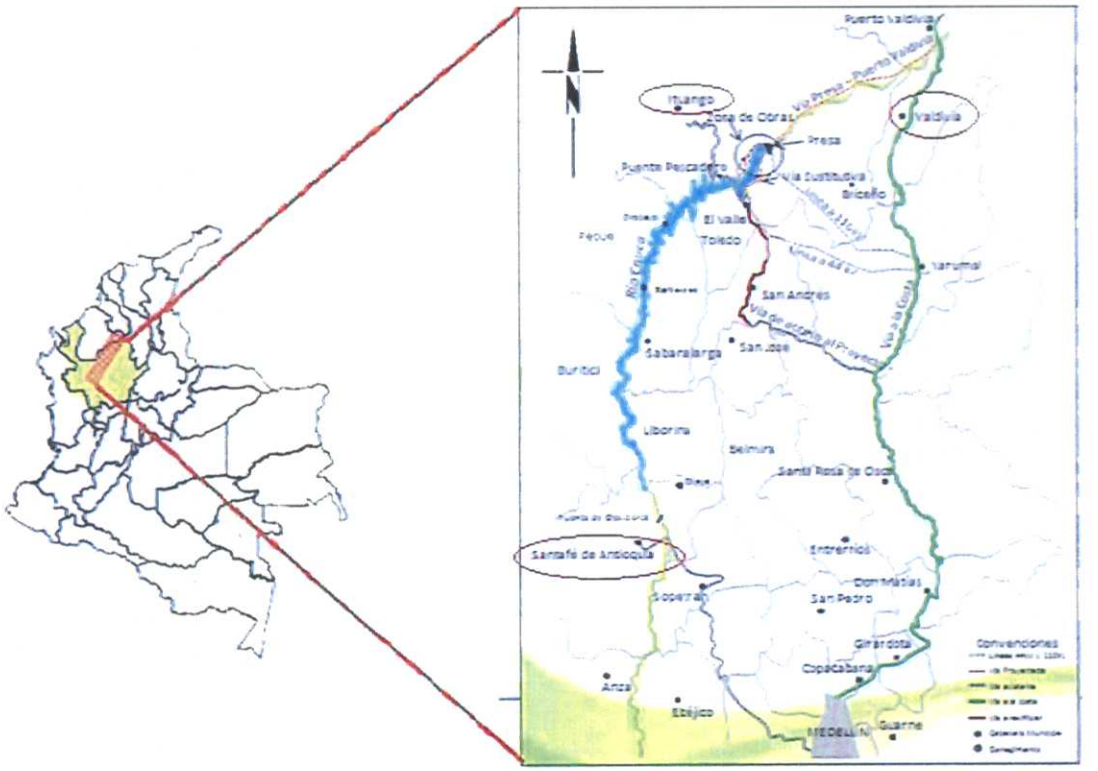

Figure 1. Location of the project in Colombia

2.2. The Plant includes a 225 m high, 550 m wide Earth-Core-Rock-Fill (**ECRF**) dam of the Cauca River, diversion tunnels for the river and a water conveyance system of tunnels to an underground power plant system in the rock mass forming the right abutment (Figure 2)

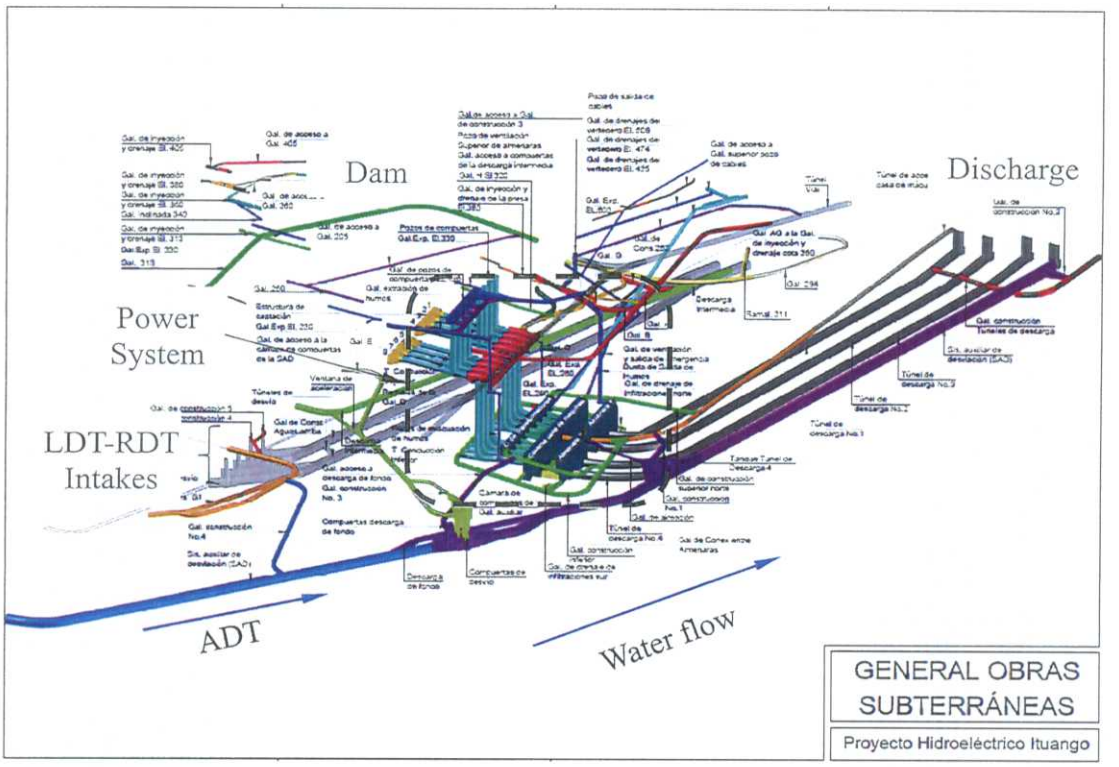

Figure 2. Layout of the underground water conveyance and power systems[1]

2.3. The power plant will generate 2,400 MW[2] and is being undertaken by *Empresas Publicas de Medellin* (**EPM**).

2.4. The tunnel where the event occurred, the Auxiliary Diversion Tunnel (ADT), was divided in four sectors, as shown in Figure 3. The sector number is used throughout the Plant to identify areas of the works.

[1] Integral (Undated) Project Layout.
[2] Ingetec-Sedic (2018) Informe final de obras principales parte 3 – Sistema auxiliar de desviación, PHI-IFF-LC1-011-R0. Page 3.

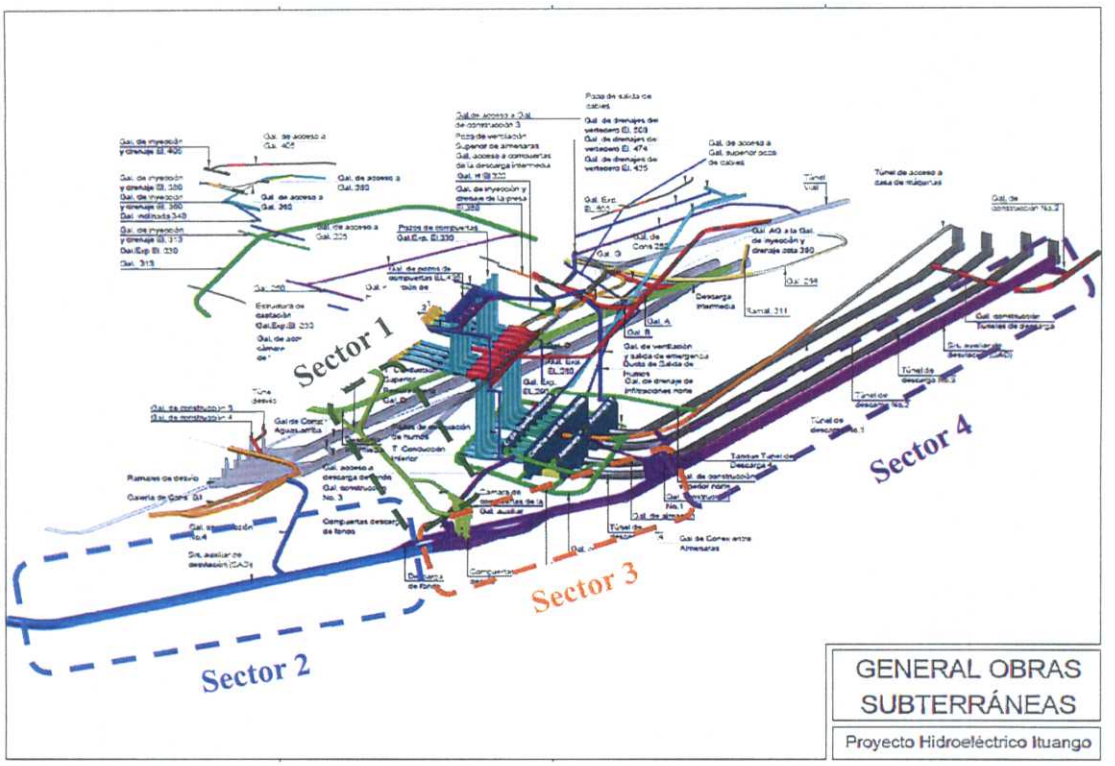

Figure 3. Sectorization of the ADT

Design and Construction of the Tunnels

2.5. The tunnels were designed using empirical, analytical and numerical methods for excavations in rock[3]. The design produced a system of support for the tunnel that varied from minimal support for very good stable rock (Type I) to the heaviest support for poor, weak rock (Type IV). The support was a combination of rockbolts[4], shotcrete[5], wire mesh[6] and arches[7].

[3] Integral (2018) Compilation of Design Calculations: I-M-2194-034-GYG-01-R0, I-I-2194-034-REV-01-R0, I-M-2194-034-EST-01-R0, and I-M-2194-034-HID-02-R0

[4] **Rockbolt** is a metal bar installed in a hole drilled into the rock and fixed against the wall of the hole (grouted) to hold the blocks and layers of rock together. It is typically 20 mm to 32 mm diameter. The grout can be cement or resin. The exposed end of the bar is threaded and a plate and nut are attached and tightened against the tunnel wall. The length of the bar depends on the condition of the rock. The bar can be tensioned (active) or untensioned (passive).

[5] **Shotcrete** is concrete that is sprayed by air pressure at high velocity against the wall of the tunnel. It adheres to the rock and sets relatively quickly to seal and stabilize the rock mass.

[6] **Wire mesh** is steel reinforcement placed against the rock or within the shotcrete to improve the properties of the shotcrete.

[7] **Arch** is a generic term for a steel beam formed to the idealized shape of the tunnel and placed against the rock to support the ground.

2.6. Construction of the Project started in September 2010 and the original river diversion works were two tunnels, the Left Diversion Tunnel (**LDT**) constructed between August 16, 2012 and June 6, 2013, and the Right Diversion Tunnel (**RDT**) constructed between July 17, 2012 and September 8, 2013, both of which passed through the right abutment[8]. These two tunnels required gates to stop the flow of river water. However, these gates could not be built in time to meet the diversion schedule. Therefore, a third diversion tunnel was proposed, the Auxiliary Diversion Tunnel (**ADT**[9]), allowing the planned diversion of water through the LDT and RDT (without gates) in February 2014[10].

2.7. The Cauca River was diverted through the LDT and RDT on February 17, 2014[10]. Construction of the ADT started in July 2015[11] and was completed in September 2017[12]. The Cauca River was diverted through the ADT on September 22, 2017[12], followed by plugging of the LDT in October 2017 and the RDT in February to March 2018[13].

2.8. The loss that is the subject of this report was a collapse of the ADT. The tunnel was a D-shape (curved roof, vertical walls and flat floor) with a nominal height and span of 14 m (Figure 4).

[8] These dates refer only to the main tunnels and not the portal works or access galleries
[9] The ADT is also referred to as the Second Auxiliary Diversion Tunnel (**SAD**) and as the Galería Auxiliar de Desviación (**GAD**)
[10] Ingetec-Sedic (2014) PHI-IFF-LC1-001-R0 Informe Final de Obra de Contrato. Page 1.
[11] Figure 14.2 PHI-IFF-LC-011-R0. July 1, 2015
[12] Ingetec-Sedic (2018) Informe final de obras principales parte 3 – Sistema auxiliar de desviación, PHI-IFF-LC1-011-R0. Page 3.
[13] Ingetec-Sedic (2019) Proceso de Cierre de los túneles de Desviación Izquierdo y Derecho. PPT Summary.