2011 Canadian Consulting Engineering Awards
Power Generation

Xacbal Hydroelectric Project, Guatemala

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Contents

PROJECT SUMMARY

The Xacbal Hydroelectric Project is located in Guatemala with an install capacity of 94 MW that generates annually 450 GWh. The project includes a diversion dam, two desilting basins, a headrace canal, a reservoir to accommodate daily peak flow, a gated intake, a tunnel of 5.7 km long, a surge tank of 13 m diameter, a steel penstock of 650 m long.

EXECUTIVE SUMMARY

The Xacbal Hydroelectric Project is located near the city of San Gaspar Chajul, province of Quiche, approximately 130 km north-east of Guatemala City. The Xacbal Hydroelectric Project is a nameplate of 94 MW (54.7 m³/s and 199 m gross head). The intake drainage area is 607.8 km² located on the Xacbal river. The project diverts flow from the creek into the headrace channel, to a classic intake through a 5.7 km long tunnel, to a surface powerhouse.

The project generates annually 450 GWh of green net energy, enough to power 400,000 homes. The project allows the offsetting 340,000 tonnes of CO_2 potential green house gas emission.

The general layout of the upstream work was developed during the project definition phase which considers topographical and geological conditions. The upstream works consist of from the right to the left bank, a right embankment dike, a spillway, an intake with a gravel trap, a desander, a headrace channel and a reservoir for peaking generation.

For construction purposes, during the first rain season, the intake and desilting basin were constructed on the left bank of the river. Then in the next dry season the dam was built leaving the central part open to pass the flood of the following season. At this time the water is diverted into the headrace channel. Finally all the works were completed in the next dry season.

The intake and spillway structures' foundation material is susceptible to erosion and scouring. The rock foundation of the dam consists of layers of highly fractured and weathered lutite that lays above fractured sandstone. This has presented many geotechnical, hydraulic and construction challenges. During flooding, water velocities in the river in its natural state are already high enough to erode the riverbed and generate bedload entrainment. For these reasons, there were legitimate concerns that the high velocity bypass flows could cause considerable erosion, ultimately undermining and toppling the structures. Therefore, plunge basins were designed to dissipate the energy with a downstream apron provided by grouted riprap. This concept was developed to ensure the stability of the intake by reducing the water velocity to the natural condition of the river.

The 5.7 km tunnel is made of a 4.69 m diameter section surrounded by reinforced concrete to resist external pressures. The maximum internal pressure corresponds to about 65 m of head at the location of the surge shaft.

The 94 MW powerhouse is equipped with 2 Francis turbine units. The powerhouse foundation is in overburden and a mat slab foundation was provided.

Another concern of the project was the stability of the powerhouse against the hydraulic forces. The draft tube was extended in order to provide a downstream backfill to balance the earth forces. This point was an innovation in the powerhouse's design.

PROJECT SUMMARY DESCRIPTION

Background

Since the end of armed conflict in 1996, Guatemala endured economic and political stability favouring its development. To fulfill the growing demands for energy, the government of Guatemala granted Hidro Xacbal Ltd (HX), a Guatemalan company, to develop the Hydroelectric project of Xacbal, which is the second largest hydroelectric powerplant of Guatemala. The project is located in the province of Quiche, in the central cordillera of the Andes, North of the Cuchumares Mountain (Figure 1). Hidro Xacbal awarded the Israelian firm Solel Boneh Guatemala the construction of the civil works of the 94 MW powerplant under an EPC contract. In November 2007, Solel Boneh granted AECOM to review and to carry out the detailed engineering. Voith Siemens was retained to supply electro-mechanical equipments under a Water to Wire contract.

Figure 1 - Location of the Xacbal Hydroelectric Project

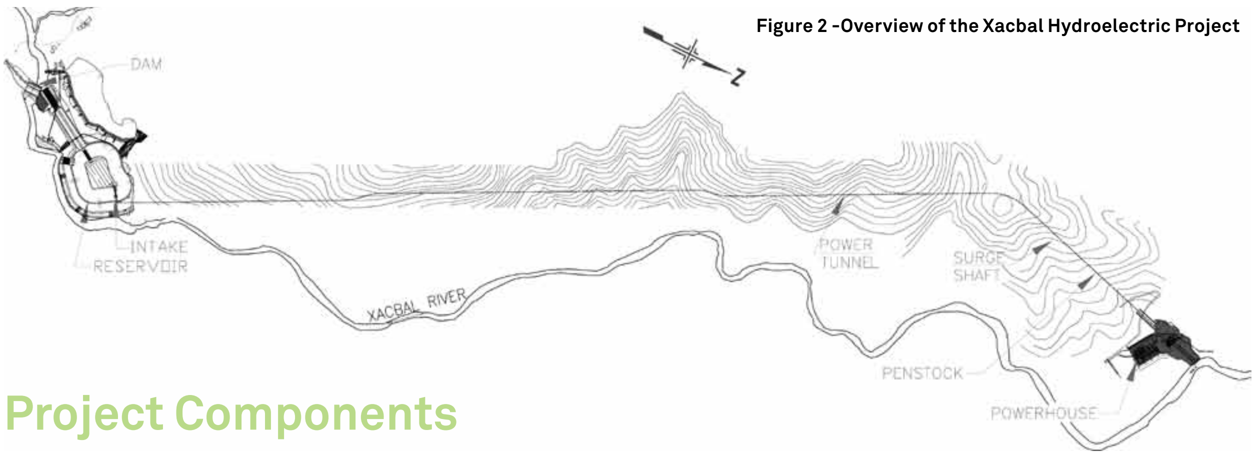


Figure 2 -Overview of the Xacbal Hydroelectric Project

Project Components

The Xacbal hydroelectric project was proposed to generate a power of 94 MW, under a design flow of 54.7 m^3/s and a gross head of 199.0 m. The project consists of an upstream works, a power intake, a penstock and the powerhouse complex including the substation as shown in Figure 2. The following sections present a detailed description of projects key components.

Figure 3 - Upstream Works

Upstream Works

From the right bank to the left bank, upstream works (Figure 3) are composed of an embankment dam, a spillway, a head regulator with a gravel trap, an intake (Figure 4) with 4 desanders, a headrace channel that conveys the water flow to a reservoir .

The dam is composed of a sill 8m high and has a span of 65m (Figure 5). This structure was designed for a return period of 1 000 years corresponding to a flow of 3000 m^3/sThe river's material is erodible and erosions may occur that would put in danger the stability of the dam and the adjacent works. Energy dissipators and bank protection have been provided to avoid any erosion in the river that can endanger the dam.

The intake consists of four chambers of the desander (Figure 6) and a gravel trap (Figure 5). Each chamber is provided with flat gates measuring 5.25 m by 4.25 m. The intake flow, maximum of 57.4 m^3/s would be controlled by gates operating during the flood period when the river flows are greater than the design flow and the excessive flow would pass over the dam.

The gravel trap is provided with a radial gate of 2.2 m by 3.0 m. The slab of the desander is implanted in the elevation 842.0 m, it is horizontal and it is located at the same level of the river and 8.0 m below crest of the dam. Downstream of the gate, a rockfill protection has been proposed to discharge the flow into the river.

Four desanders have been proposed to eliminate greater sediments of 0.4 mm. They have a length of about 80 m and 12.0 m wide. Its depth is 10.95 from the water level in normal operation. The crest level of side walls is 851.0 m. Bottom of the desanders have a 4% slope according to design instead of 2% as is described in the specifications of bid documents to improve the sediment flushing operation.

Each desander is provided with a flat gate of 2.0 x 2.0 m implanted in a gallery below of the channel between the desander and the reservoir. The flushing pipes are made of square section of 2.0 m per side. Downstream side is located to 2.0 m over the river bed. The flushing pipe was covered by filling material that ranges from 10 m to 2 m. A rockfill protection has been proposed at the exit of this structure to prevent erosion.

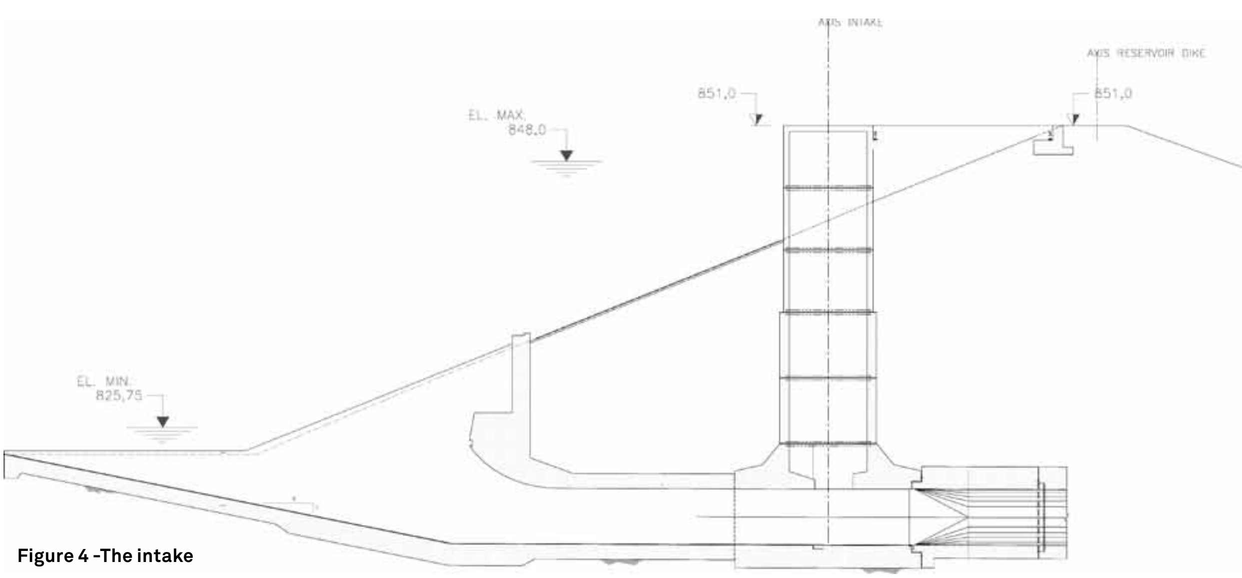


Figure 4 -The intake

The headrace channel is trapezoidal in shape, covered with a concrete slab 0.3 m thick. Its length is about 200 m, its width at the bottom is 10.0 m and side walls with a slope of 2.5H:1V.

The embankment of the headrace channel has a trapezoidal shape. Its length is 200 m, width at top is 10.0 m and side walls with a slope of 2.5H: 1V. The channel ends at its downstream with a step channel of 20.0 m with a slope of 2.5H: 1V and concrete blocks to dissipate water energy. The transition has a trapezoidal section, covered with concrete slab of 0.40 m thick.

The reservoir (Figure 7) has a volume of 750 000 m^3 for peaking generation. The reservoir is formed by an earth dike in adjacent zone of the river and encroaches into the mountain on its left bank. It is provided with a geomembrane to ensure its impermeability and protected by a geotextile. Related works of the reservoir are the spillway, a sub-surface drainage, a drain pipe and a diversion structure of the stream that drains the flow to the reservoir of north-west side.

The normal maximum operating level is 848.0 m and the earthen dike crest elevation is 851.0 m. The minimum operating level of the reservoir is 825.0 m.

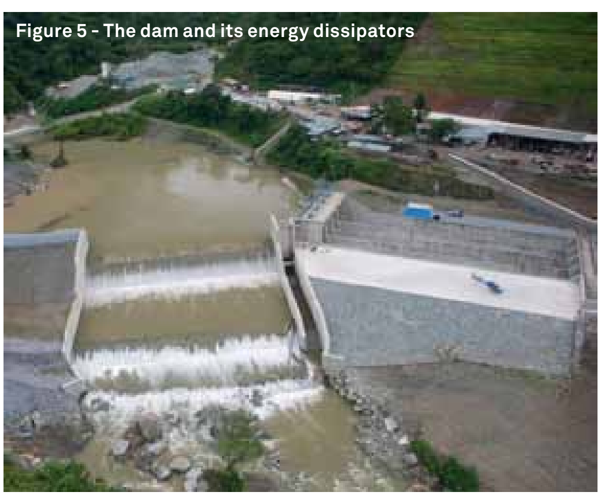


Figure 5 - The dam and its energy dissipators

The spillway floor has been proposed to the elevation 848.50 m and 32.0 m length. Its capacity is equal to the equipment flow plus 10%, it means 63.1 m^3/s. The spillway channel follows the slope of the earthen dike and has a concrete lined and ends with a ski jumping to leave the river flow. A device to dissipate the energy has not been proposed because the presence of rock in the river left bank and the flow is delivered to the elevation 828.0 m, corresponding to the elevation of the riverbed. The spillway has been checked for an exceptional case of a flood of 1000 years of return period and all intake gates are open and in this extreme event the free board in the reservoir is 1.5 m.

Sub-surface drainage system consists of a perforated pipe, which should be designed for inspection and be provided with instrumentation systems. The discharge pipe from the reservoir is formed by a pipe of 1.0 m diameter embedded in concrete. Its line begins near the water intake to the tunnel, to elevation 820.0 m and should continue to find the Xacbal river. It should anticipate this line by continuing toward downstream and it should be 2 m to 3 m above the river bottom.

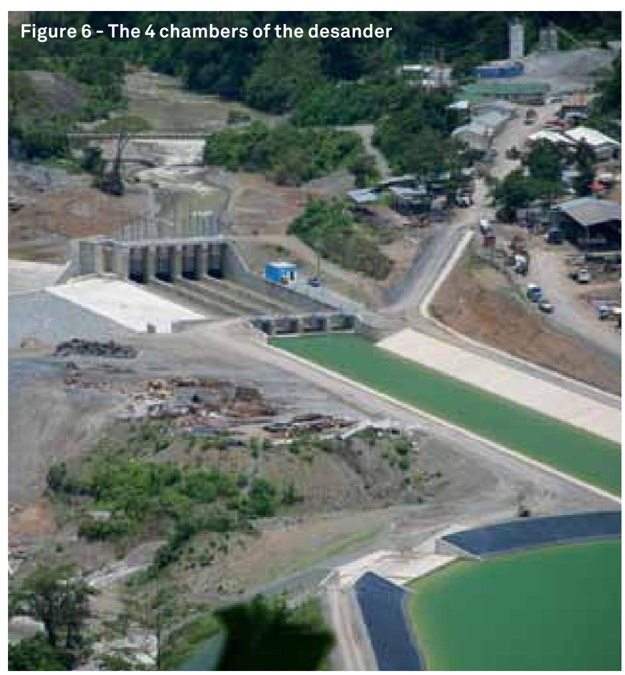


Figure 6 - The 4 chambers of the desander


Figure 7 - The reservoir

Protection works and expansion of the river bed

In previous studies it was proposed to excavate the river bed so as to increase the capacity of the river. Also, retaining walls were anticipated to protect both the left and right banks of the dike and to protect likely unstable zones, especially in zones of potential sliding.

For safety conditions, it is not advised to implant concrete retaining walls to slope into the river. These structures are very rigid and are exposed to bottom erosions that could be decreasing their stability or, otherwise, the foundation of these walls would have to be as deep as to avoid erosions on their foundation. In general, for protective installations in the river, flexible structures have been proposed and, if damage appears, they could easily be repaired and this concept has been applied.

Power tunnel

The power tunnel is formed by the intake in the reservoir, the tunnel itself and the surge shaft (Figure 8). The intake is formed by a steel pipe of 4.69 m in diameter embedded in concrete and its pipe axis is located at elevation 819.225 m. A gate chamber has been implemented to 15 m upstream of the axis of the dike.

The horseshoe-shaped tunnel has a length of 5.7 km with a circular interior section of 4.69 m in diameter and covered with reinforced concrete to support the external pressures. Downstream sections of the tunnel merges with the surge shaft of 13.0m in diameter. The tunnel will support an a maximum internal pressure of 65 m in height from the surge shaft.

Figure 8- Reinforcement in the power tunnel

Penstock

The penstock has a 3.55 m diameter and is buried under fill of 1.0 m high. At the end, to about 80 m upstream of the manifold (bifurcador), a change of direction with filling material of the order of 15.0 m of thickness has been implanted (Figure 9).

Powerhouse and Substation

The powerhouse is located in the left bank of the river and it is protected for a flood of 3500 m³/s (1000 years of return period). The power of 94 MW is generated by two units of Francis type. The powerhouse foundation is on overburden (no rock has has been found) and special foundation treatment has been applied and finally a mat slab foundation has been found to be the most appropriate. In order to stabilize the powerhouse structure, the draft tube has been extended in order so that backfill can be placed and help for the stability. This criteria produced appreciable economy in the project (Figure10).

Figure 9 -The valve of the penstock

Figure 10 - Upstream view of the powerhouse

Innovation

Driven by a strong creative spirit, our technical team came up with innovative approaches to respond to the ongoing challenges.

New applications

High hydrostatics pressures create a high loads that push the powerhouse downstream (Figure 11). To resist against those loads, the powerhouse had to be firmly rooted in rock. Once again, the rock quality was a major concern and our engineers had to be imaginative. The solution consisted of two aspects:

- to construct a foundation slab of 2.5 m thick in the specific area to evenly distribute the vertical force produced by the vibrations of turbines
- use the penstock located upstream and downstream of the powerhouse to fix it.

To compensate for the high hydraulic forces toward downstream, the engineers had the brilliant idea to extend the draft tube by 30 m to increase the bearing surface of the embankment. This concept stabilises the foundation and offers resistance against longitudinal loads. This solution balanced the forces acting on the powerhouse and reduced the amount of concrete required.

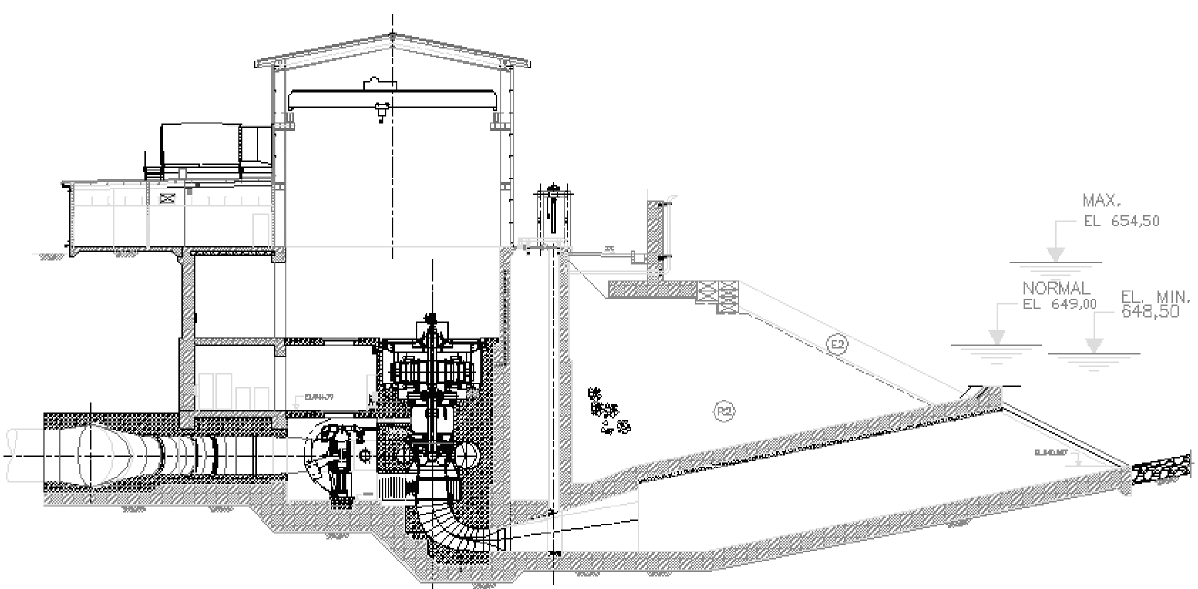
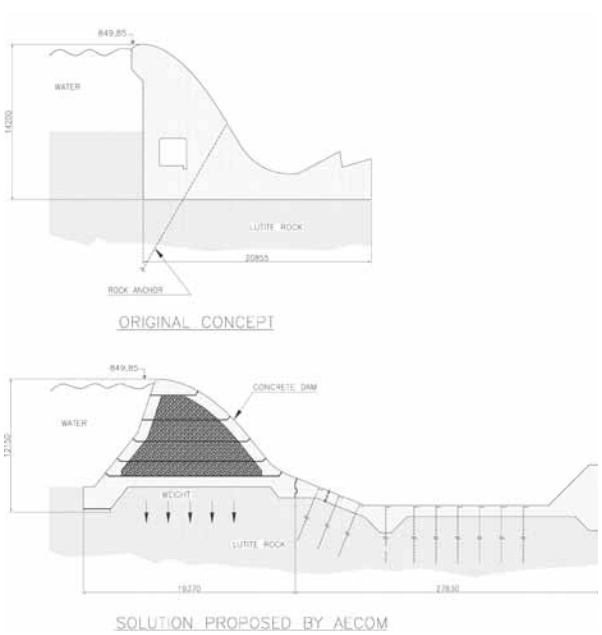


Figure 11 - The powerhouse

Originality

The original concept of the dam considered the installation of anchors (Figure 12). We changed the concept to assure the stability of the dam by using gravity forces. AECOM engineers tend to favour the design of a freestanding dam, since there is high seismic activity in Guatemala, anchors can move over a long term period. Also the poor quality of lutite rock under the dam bedding did not allow injections galleries to be implemented, which are always required when installing anchors. Therefore the gravity dam avoids instability caused by karstic rock found on site and ensures a greater sustainability. The gravity dam used almost an equivalent volume of concrete than the structure originally planned.

Figure 12 - AECOM's innovative approach towards optimizing the dam's geometry

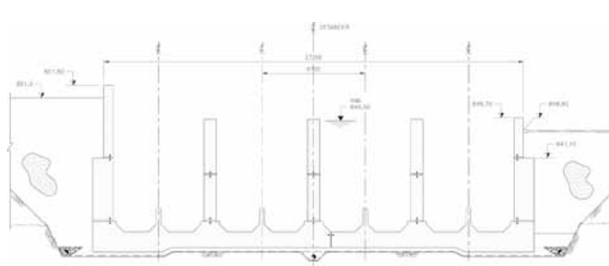


As for the downstream protection there were legitimate concerns about the high velocity (15 m/s) at the toe of the dam that could cause considerable erosion, ultimately undermining and toppling the structure. The team proposed a creative design consisting of stilling basins. The concept has allowed to moderate flow velocity to similar natural condition.

Another example of adaptation has consisted in replacing the "V" bottom shaped of a conventional desander (Figure 13) that required deeper excavations and a longer drain pipe for a horizontal bottom shaped concept. Thus the economic gain allowed doubling the performance in the amount of desilting basin. To meet the hydrometric requirements of a torrent, a screened wall was immersed in front of the desanders to stop rocks and return them to the river through an outlet gate.

The tunnel was also drilled in a crumbly karstic rock. Therefore, it was paramount to avoid leakages by improving watertightness of the tunnel. As a result, the 5.6 m exterior diameter horseshoe shaped tunnel was lined with reinforced concrete along its entire length and reinforced with steel arches on almost 20% of its length.

Figure 13 - The horizontal bottom of the desander (transversal view)



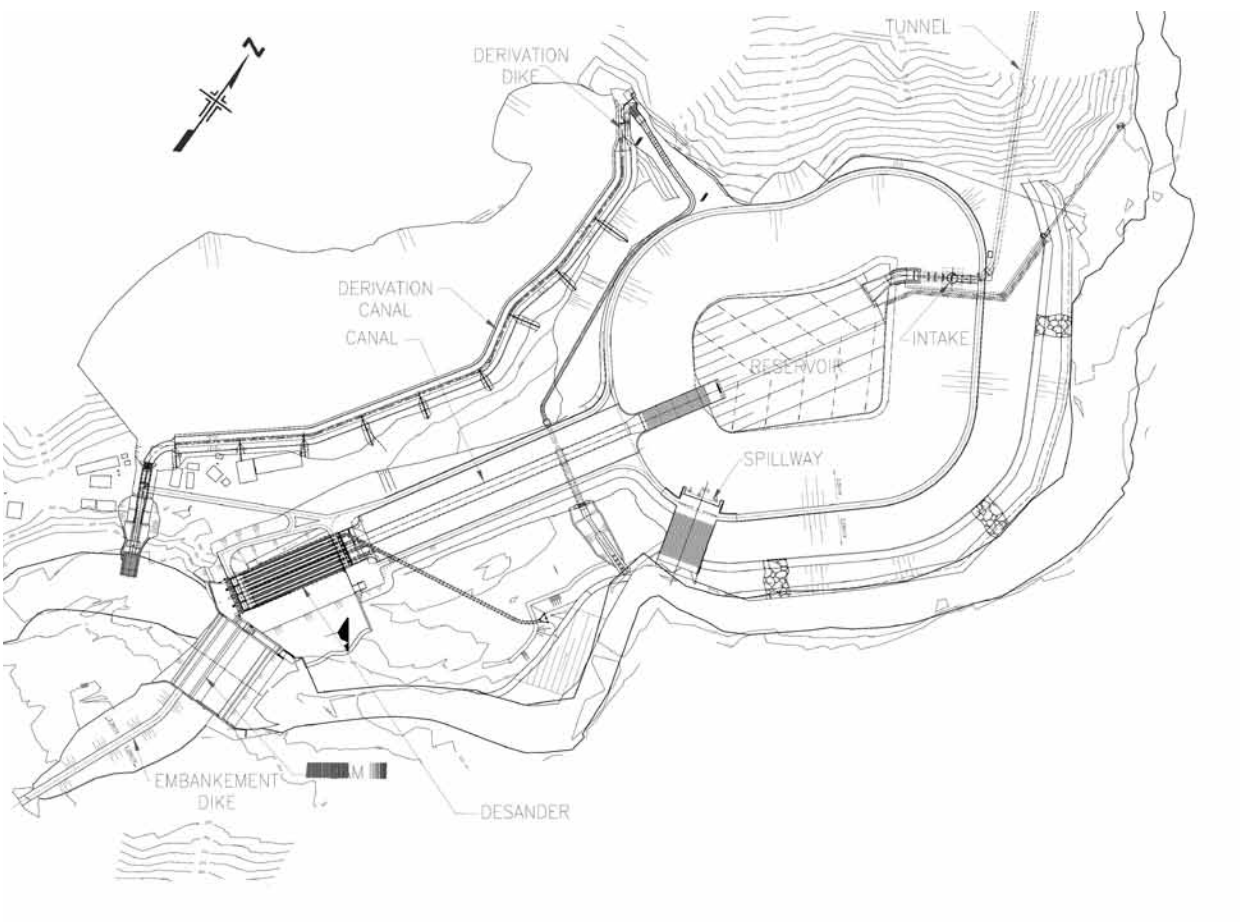
COMPLEXITY

Problems and constraints

AECOM engaged a fast track regime of optimisation studies of the project and of detailed engineering works, while participating in all relevant phases and activities.

The unique hydrologic aspects of Rio Xacbal rendered the analysis of hydraulic behaviour complex. This is due to the fact that the discharge is greatly influenced by tropical rains which generate significant floods and displaces sediments. Therefore, it was necessary to consider the large variations in water levels and discharges (flash floods) in the analysis as well as in different design phases, such as those for cofferdams and spillways.

Figure 14 - Upstream structures



There were many outstanding issues with upstream components (Figure 14). The initial bid envisioned anchoring the dam foundation to rock. The challenge was to determine a method that would stabilize the dam without using anchors, given that the mechanical properties of the lutite rock foundation was insufficient to ensure long term integrity of the structure.

Another hurdle the Xacbal team faced was ensuring that operating two desander basins would not prevent the powerhouse from functioning without interruption.

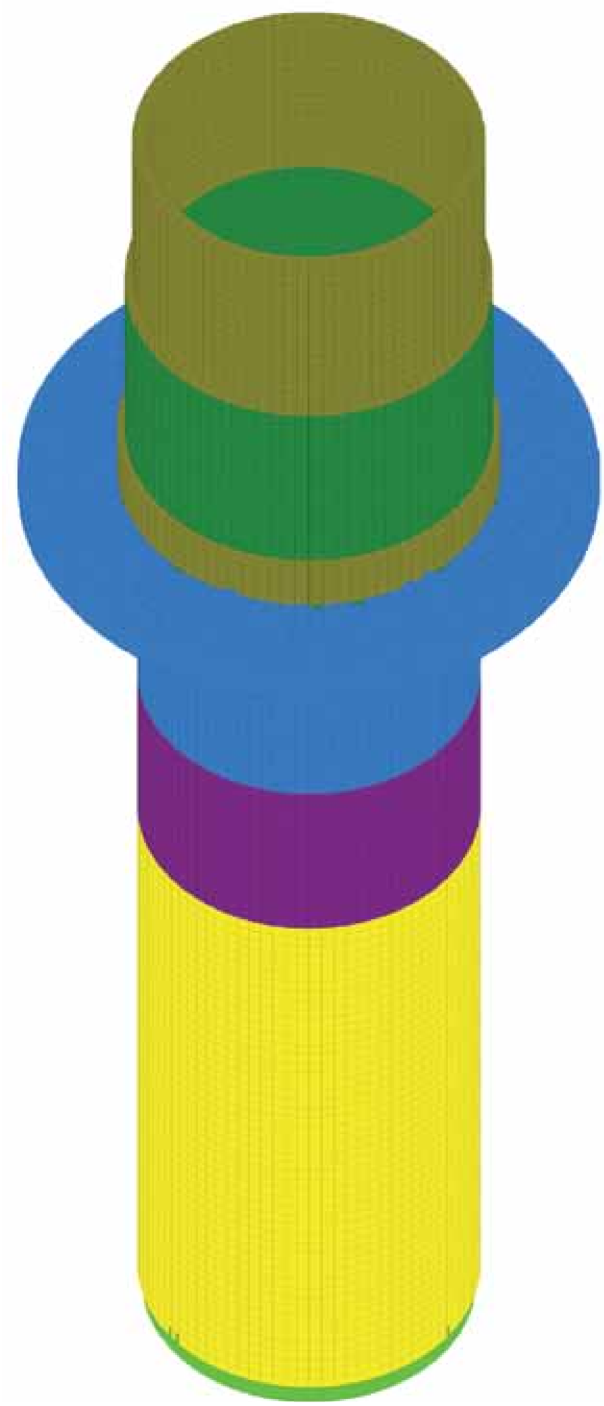
The absence of a stilling basin meant that the speed of water at the foot of the dam approached 15m/s, which was too great and could erode materials and the downstream riverbed. The concept of the basin had been conceived to tame the flow of water and to bring its speed to back to normal conditions.

There were as many challenges in the downstream components. Extensive microseismic tests were conducted to determine rock properties which were used to optimize tunnel design. Over a 5 km span, the quality of the rock varied from poor to very good. In some locations, the presence of karstic rock, which is brittle by nature and conducive to water exfiltration (upon contact with water, the rock disintegrates) created a challenge.

Connected to the power tunnel is the surge shaft (Figure 15), of which more than 2/3 its height is embedded in rock, dissipates pressure exerted in the penstock and during a backflow. The dimensioning of the surge shaft was developed with the software Hytran, which calculates accurately the maximum water level during a surge.

The AECOM team of engineers wanted to avoid using costly expansion joints, so they decided to bury the penstock. The backfilled buried trench protects the penstock from thermal shock which leads to steel expanding, thus rendering the use of these joints necessary. Apart from its humble dimensions, this method bypasses the need to segment the penstock which would have been essential had expansion joints been applied.

Figure 15 - 3D structural modelling of the surge shaft



As with many of Xacbal other structural components, the quality of the foundation, a thick layer of overburden and incompetent rock, was an outstanding factor in the powerhouse design. The hydrostatic load produced upon gate closing exerts an enormous force that pushes the powerhouse downstream. The Xacbal team had to come up with a solution that would resist these forces and reduce the amount of concrete used.

Climate and Site Conditions

One of the greatest challenges was adapting the construction phases to the cyclic humid and dry climates of the mountainous Guatemalan jungle (Figure 16).

During the first season of rain, the intake and gravel trap were constructed on the left bank of the river. The following dry season, part of the overflow dam was erected while leaving the central monolith part open so as to allow the passage of the river foreseen for the next humid season. Always during the dry season, a floodway redirects the river on the right bank, which permits the final stages of dam construction. In the next humid season, the river runs through the floodway and the gravel trap. The dry season follows, and the river passes through the gravel trap allowing for the retaining dike to be constructed on the river bed on the right bank.

ENVIRONMENTAL IMPACT

The Xacbal Hydroelectric Project provides clean, renewable and emission-free energy. Its annual energy production is estimated at 450 GWh, which allows to provide “green energy” to more than 400 000 homes annually. By comparison, a thermal station of the same power capacity as that of Xacbal would generate 340 000 tonnes of carbon dioxide to atmosphere whereas Xacbal powerhouse does not produce any greenhouse gases during its normal operation.

Terrestrial environment preserved to the maximum

Run-of-river installation allows to reduce the environmental impact: a minimal storage reservoir was created, which limits the encroachment of upstream works. Moreover, powerhouse and switchyard are located in an enclave site, which restricts the presence of invasive structures. Since many structures of the project are underground, only the upstream works, the powerhouse and transmission lines are visible.

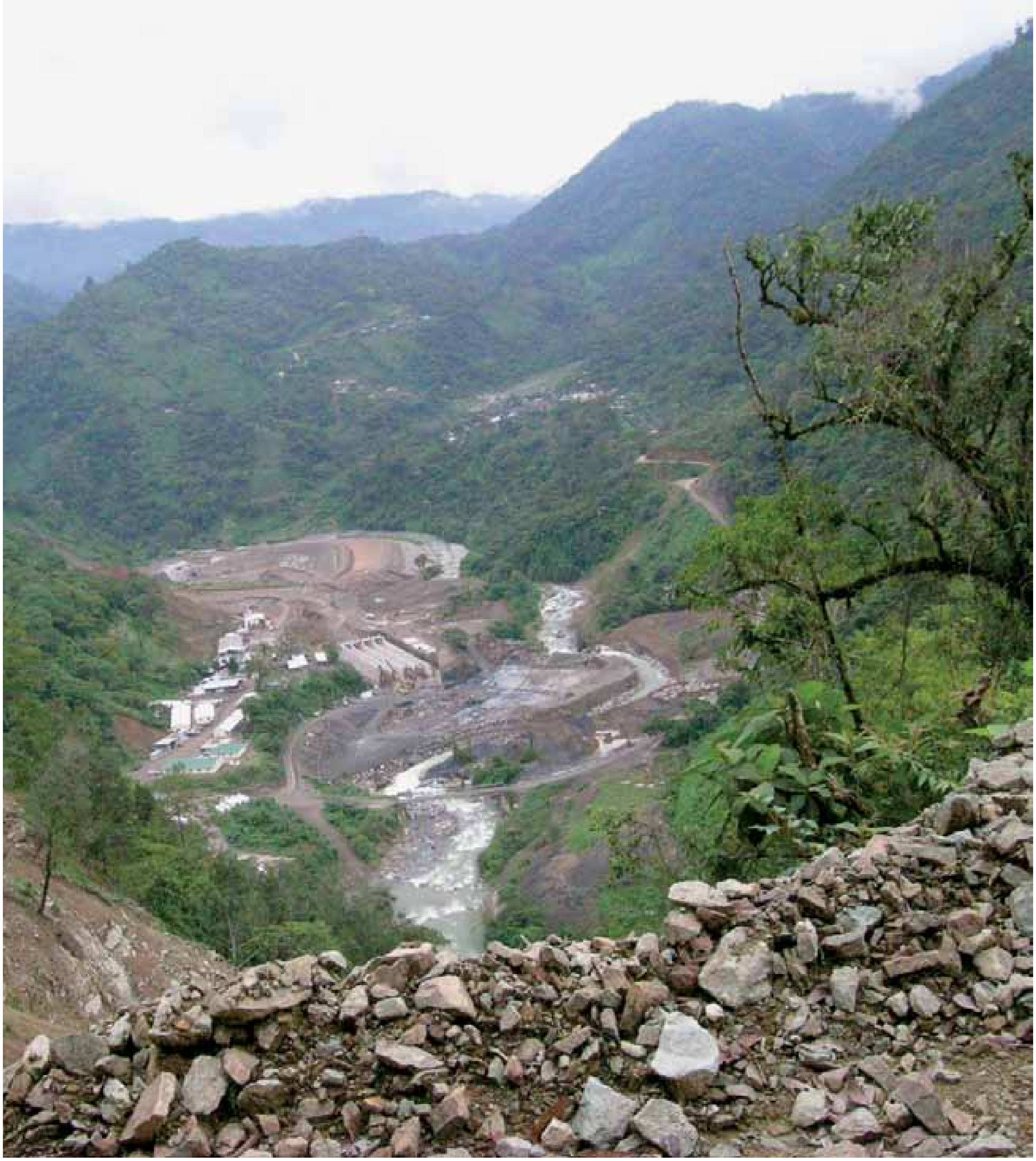
Shaking up ideas instead of mixing concrete

Also, the AECOM team had made efforts of optimization by reducing the concrete volume used especially for the works located upstream and for the powerhouse.. For example, in the basin, excavated material was re-used in the dam to form the reservoir. This approach has eliminated a large part of negative impacts related to the manufacturing and transport of materials (120 km).

Increasing the river’s pulse without changing its rhythm

Upstream works, extracting damaging sediments to equipments and diverting part of the river flow towards a tunnel, increases, by this underground passage free of blockages, the river’s pulse that gives life to the powerhouse. Once the river passes through two groups of Francis turbogenerators, water is returned to its bed without any effect to its rhythm

Figure 16 - The Xacbal Hydroelectric project nested in the Guatemalan jungle



Social and economic benefits

The Xacbal Hydroelectric Project is part of Guatemala's renewable energy program of the national energy plan whose main goals are obtaining an energy autonomy and promoting development of renewable energy projects in respect to local people.

During the construction phase, the project had as direct benefit the hiring of 200 local people at full time on the construction site.

Energy produced from Xacbal will help appreciably to reduce energy dependence of Guatemala and to lower electricity prices. Locally, the project allowed a more affordable energy source and the construction of 5 km of new roads replaced small access rural roads that were impractical. It is evident how these infrastructures are a blessing for the local farmers, in particular for coffee producers and their families. The project had a magnetic effect in the region where the construction of houses, schools and small businesses are implemented.

Meeting exceeding owner's/ client's needs

Budget

Since AECOM was granted a fixed price contract, this presented to be a daily challenge. Furthermore, to avoid unforgiving penalties, structures had to be erected within 30 months after the signing of the contract. Despite this obstacle, all professional services were delivered according to the Solel Boneh's 250 million dollar budget. In addition, minimal pressure losses from the structures generated an additional energy production of 2%, which is remarkable.

Schedule

From the start of the mandate in November 2007 to the operation in May 2010, the Xacbal team proved its efficiency by delivering construction drawings in parallel to the hasty rhythm of construction while providing efficient and quick solutions to problems encountered on site. All plans and specifications were completed more than one year before commissioning the project. This allowed the contractor to deliver the project on time and avoid costly penalties.

Project human resources

To provide superior engineering services, AECOM selected a team multi-disciplinary team ranging from the most seasoned experts to the most junior of junior engineers. The design team had local and national expertise to its credit, as well as international experience such as in India and Latin America. More than ten fulltime engineers, with their know-how and dedication, gave AECOM the tools to overcome the challenges that awaited them in the heart of the Guatemalan mountains. In addition, four technicians from AECOM's New Delhi office were transplanted to Montreal for five months. They had good expertise since topographic conditions in Guatemala were similar to those in northern India.

It was due to the cohesion and synergy of our personnel, on-site presence, with close collaboration between the client, the contractor and the technical team that the Xacbal Hydroelectric Project was successful.

Impact on the canadian consulting engineering profession

Beyond the inherent challenges of engineering, there is a method of evaluating a situation and to understand the potential of future achievements in the given geo-political context.

Collaborating with our Indian colleagues shows that the engineering profession has no borders, as transferring and exchanging knowledge is a win-win situation for all parties involved.