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Economic and energy loss minimization: design and repair works after failure of the Pucará headrace tunnel in Ecuador

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ABSTRACT: A landslide occurred in September 2011 caused damages to the final 300 m stretch of the 5.5 km long, 2.6 m diameter headrace tunnel of the Pucará power plant in Ecuador. Open fissures and dislocations appeared within the concrete lining of the tunnel. The plant had to be shut down after 34 years of its commissioning. Engineering and repair construction work were immediately undertaken by Lombardi Ltd. and Odebrecht, respectively. A concrete-lined bypass tunnel (519 m, $\Phi = 2.70$ m) with a 380 m long access tunnel was selected as the best solution to overcome the problem. The damaged tunnel was proposed to operate as a drainage to help with landslide stabilization. The poor quality of rock required controlled excavation and continuous support by means of steel ribs and reinforced shotcrete. Studies were carried out to minimize economic losses caused by the plant's closure and by possible reservoir water spillage. It was proposed to install a fibreglass reinforced plastic (GRP) pipe ($\Phi = 1.60$ m), within the damaged tunnel, to allow the operation of one turbine with its full capacity of 36.5 MW, during the 7-8 months that were estimated for the construction of the bypass. This solution was implemented over a period of 4 months and the plant became partially operative on November 11th, 2011. During the period of time required to connect the bypass with the headrace tunnel, the incoming water in the reservoir is stored with the purpose of future energy generation. The plant is expected to resume its normal operation in the fall of 2013.

1 Introduction

The Pucará hydroelectric power plant belongs to the "HIDROAGOYAN Business Unit", which is part of the "Corporación Eléctrica del Ecuador" (CELEC EP). The plant is located in the province of Tungurahua, 35 km East of Píllaro city and 160 km South East of Quito, the capital city of Ecuador. The plant was constructed in almost 5 years and it was commissioned by the end of 1977, as the first main plant of Ecuador's power supply system.

After 34 years of normal operation, the plant had to be shut down in September 2011, after being affected by a landslide of large scale of the slope located adjacent and parallel to the final stretch of the headrace tunnel, associated to a geological fault. The landslide affected about 300 m of the final stretch of the headrace tunnel.

As consequence, damages in the concrete lining, such as open fissures and displacements occurred in this tunnel stretch, causing such a critical situation that the plant was prevented to be in operation.

The suspension of the plant caused huge economic losses to the country, not only because of the lack of energy production, but also because of the waste of spilling water from the reservoir. Therefore, Hidroagoyán authorities declared the state of emergency for this plant status and decided to rehabilitate the tunnel as soon as possible. Engineering and construction work was immediately contracted out to Lombardi S.A. and Odebrecht, respectively.

The engineering criteria for reparation proposed a safe solution that could be implemented in the shortest timeframe, and that would assure an extension to the useful lifetime of the plant.

Figure 1. The landslide that affected the headrace tunnel

2 Principal characteristics of the Pucará power plant

A 41.20 m high rockfill dam, with its crown at 3’569.20 masl, transformed the Pisayambo lake in a larger reservoir (Figure 2) with an effective volume of 90 million m^3 between its maximum and minimum operation levels of 3’565 and 3’541 m asl, respectively. The effective storage capacity of the reservoir guarantees the Pucará plant to generate an annual average power of 230 GWh..

Figure 2. The Pisayambo reservoir

An embedded intake located at the left slope of the reservoir at 3’537 masl, leads the water through the headrace tunnel towards the power house. The headrace pressure tunnel is 5’475 m long and completely concrete lined, with circular hydraulic section $\Phi = 2.60$ m. The design flow is 18.6 m^3/s. The static internal pressure within the tunnel varies between 30 m at the intake and 65 m at the surge tank bottom. The dynamic pressure near the surge tank reaches 90 m. The concrete lining of the tunnel is partially reinforced with steel bars, in especially the final part, where rock coverage is reduced while internal water pressures are higher. The last stretch immediately upstream of the surge tank, down to the butterfly valve, is steel-lined and it includes the surge tank, which is 117 m high, with an internal diameter of 5.00 m, with an orifice of 2.40 m in diameter.

The pressure shaft is steel-lined, 685.5 m long, inclined 50^0, with internal diameters 2.20 m and 1.90 m, and ends with a bifurcation to feed the two turbines.

The underground power house of the plant accommodates the two Pelton turbines at 3’086 m asl. These turbines are of vertical axis type with six injectors. The plant exploits a gross head of 479 m and has an installed capacity of 73 MW.

The turbinated flows are returned to the Yanayacu River by means of a short free flow discharge tunnel followed by a short discharge channel.

3 Damages in the headrace tunnel and design criteria adopted

The area in which the landslide occurred (Figure1) is characterized by a very complex geology with the presence of many faults, discontinuities and open fissures. In general, the rock in this zone shows to have a high degree of alteration and low resistance characteristics. Additionally, the zone is situated in the so called “Pisayambo Seismic Nest”, in which more than 400 seismic events with magnitudes less than 4 degrees in Richter’s scale and low hypocentre depth are registered annually.

In this geological environment, characterized by a fractured rock mass, the location and shape of the fissures recognized along the damaged tunnel stretch indicate that their presence is due to tensile stresses caused by the internal water pressure.

In addition the actual rather superficial tunnel position with only 40 m of lateral rock coverage and a vertical overburden as low as 55 m, leads to a geomechanical rather unfavourable situation.

It appears that actually seismic loads, excessive loads caused by water losses due to filtration, as well as intensive rainfalls, had also contributed to the slope instability.

The proceeding fissure propagation, destroyed/affected the arch effect in the concrete lining of the tunnel. As consequence, a compression of both semi-circumferential concrete parts occurred, which finally caused rock spalling at the tunnel roof, where the maximal compressive stresses developed (Figure 3).

Figure 3. Stretch of damaged headrace tunnel and fracture detail

According to the technical experts of Lombardi Ltd., the position of the affected headrace tunnel was not adequate particularly with respect to its limited distance to the slope surface (Figure 4). It appeared that the actual lateral and vertical rock thickness was not sufficient to guarantee the long term stability of the tunnel. Furthermore, due to the water circulation, the strength and deformation characteristics of the surrounding rock mass had been progressively reduced.

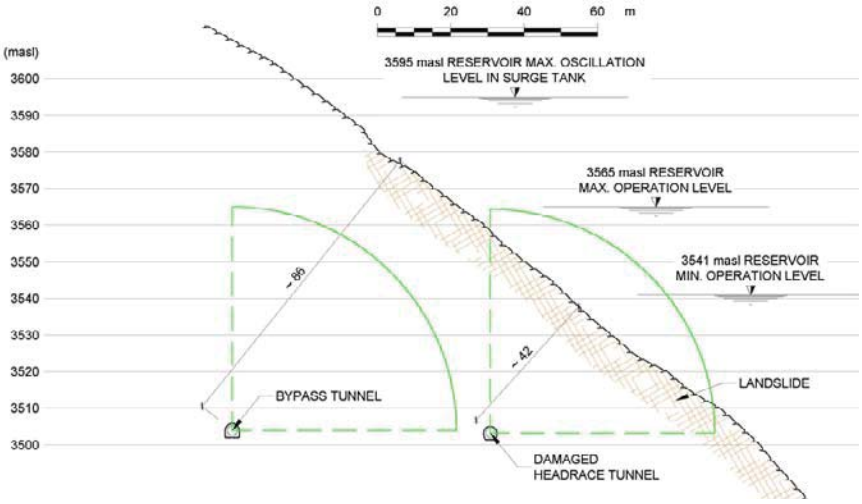

Figure 4. Stretch of damaged headrace tunnel

Because of the urgency for a rehabilitation design of the tunnel, taking the present and future slope stability into account, and based on several technical site visits as well as variant studies, Lombardi specialists proposed the construction of a bypass to the affected tunnel.

4 Actions undertaken for reparation

After assessing the damages withn the tunnel and subsequent shut down of the plant, CELEC EP authorities took immediate actions to deal with the problem. Finally, in September 2011 the state of emergency was declared for the plant. At the same time, CELEC EP asked for technical advice of national and foreign engineers, including a visit with an expert assessment of the damaged stretch of the tunnel, in order to receive proposals for the definitive reparation of the tunnel, as fast as possible.

The execution of field investigations, basic, final as well as the detailed construction design was commissioned to Lombardi Ltd.. The supervision of construction work was performed in close collaboration with the technical personnel of CELEC EP.

According to the repair concept proposed by Lombardi Ltd., the companies CELEC EP and Odebrecht signed the construction contract for the rehabilitation of the tunnel, in October 2011.

5 Rehabilitation of the headrace tunnel

Lombardi Ltd. performed all field investigations, basic studies, final and construction design in parallel with the construction works..

Taking into account the results of the field investigations (topography, geological and geotechnical rock characteristics) the basic concept for the bypass was optimized (Figure 5).

To avoid the risk of hydro-fracturing, the main stretch of the bypass runs parallel to the affected tunnel, displaced 70 m into the mountain, providing enough lateral and vertical rock overburden to the bypass tunnel.

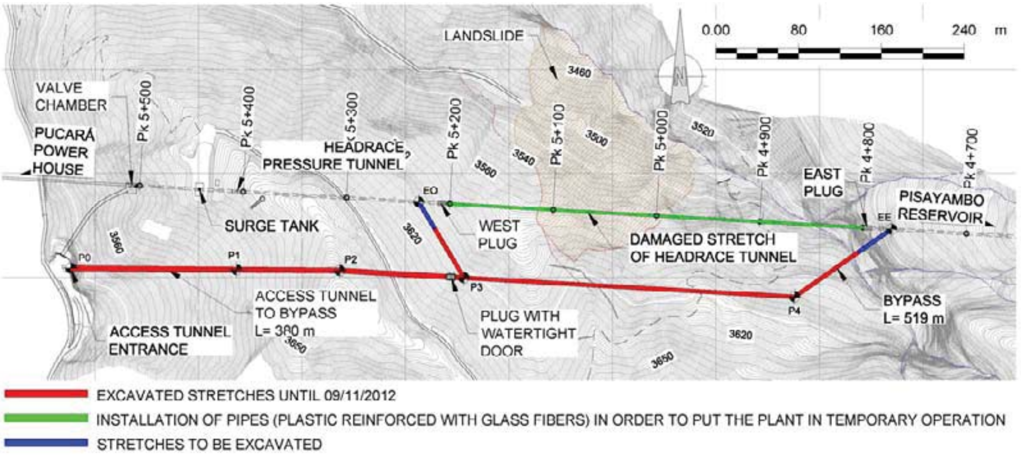

Figure 5. Working scheme during construction phase

The optimized rehabilitation solution involves the construction of a bypass with a total length of 519 m, concrete lined with an internal circular section of diameter 2.70 m.These characteristics and dimensions were chosen in such a way that the plant works with the same hydraulic performance during normal operation like the pre-existing pressure tunnel before. Because of its design, the bypass requires the excavation of a 380 m long access tunnel with a D-shaped cross section of 5.00 m x 5.00 m .

The proposed solution also allows the tunnel stretch to permanently drain the nearby rock slope. In this way it provides also a certain slope stabilization. For this purpose, drainage holes were systematically drilled along the affected tunnel. The drainage water is discharged by means of a pipe embedded within the concrete base of the bypass as well as the concrete plugs, and is subsequently led through a ditch located at the base of the access tunnel. Furthermore, in order to prevent the deterioration of the most strongly damaged tunnel part (70 m), support measures, such as circumferential steel ribs around the inside of the concrete lining and 15 cm of shotcrete with steel mesh reinforcement were installed.

The poor quality of the rock mass along the access and bypass tunnels required controlled excavation and continuous support with steel frames and reinforced shotcrete.

The bypass tunnel was excavated to the final 3.80 m x 3.80 m D-shaped section. The use of rock bolts as support measures was not possible because of the high degree of rock fracturation. Accordingly, the excavation required continuous support by means of steel ribs and shotcrete reinforced with steel fibres or/and steel mesh. The minimal shotcrete thickness was 25 cm.

The final structural concrete lining of the bypass was designed to be 30 cm thick, reinforced with steel bars to resist the internal water pressure. To avoid water leakages, an impervious elastic membrane was to be placed between the support and the structural linings.

The affected tunnel was planned to be isolated from the bypass by means of two concrete plugs provided at its ends, next to the east (EE) and to the west (EO) junction points.

A concrete plug at the end of the access tunnel was designed to allow the normal flow of water through the bypass tunnel for normal operation of the plant. This plug incorporates a 2.00 m x 2.20 m gate for inspection purposes of the headrace tunnel.

Concerning the excavation works, the installation facilities and material deposits were located close to the entrance of the access tunnel, in this way minimizing the environmental impact. Other logistic installations such as the concrete plant, laboratory, offices, sleeping accommodations, dining room, were placed in and around the Pucará camp, located outside of the power house.

6 Temporary operation of one turbine

The outcome of the field investigations and the execution of excavation and support measures within the access tunnel, with an average advancement of 2.4 m/day, provided by and by a better understanding of the weak rock conditions for the bypass tunnel construction. Therefore, in June 2012, the working schedule was adjusted, while the completion of contract was foreseen for autumn 2013. That means, that at that time, there was still 1.5 years of construction time before the plant could become operational again.

With the objective to reduce the closure period of the plant and the tunnel rehabilitation cost, a feasibility study was carried out to analyse the possibility of operating one turbine as soon as possible. For this purpose, the installation of a fibreglass reinforced plastic (GRP) pipe inside the affected tunnel was designed.

The pipe should be easy and quick to be installed. Single pipes of limited length allowed for an easy transportation to the site and to be mounted and placed on individual prefabricated steel supports. These pipes s were provided with O-ring rubber seals in their junctions.

In this way, the economic and energetic losses caused by the plant being decommissioned can be minimized. This solution also prevented any spilling of water from the reservoir and helped to utilize part of the r effective reservoir volume. The turbine operates with its maximum flow of 9.3 m^3/s, to its maximal capacity of 36.5 MW for 24 h/day for 7-8 months while the bypass is under construction. During the time when the plant remains shut down for connecting the by-pass tunnel with the undamaged headrace tunnel, the reservoir will be supplied by the water coming from the Yanayacu River, storing water for future normal energy generation.

Regarding the length of the bypass tunnel, three alternative length for the GRP pipe were studied: 500 m, 415 m and 230 m. Hereby, all costs involved in the construction of the bypass tunnel, the access tunnel and the pipe, as well as the execution time for each alternative and the corresponding energy benefits produced were taken into due consideration. Finally, a pipe length of 415 m was selected as the best one.

After the technical and economical feasibility of this project, as well as the great benefits in case of execution were verified, the proposal was approved by CELEC EP and it was immediately implemented.

A GRP pipe, DN 1600 mm, PN 10, produced in Ecuador by RIVAL, was installed within 4 months, allowing the plant to go in temporary operation on November 11th, 2011. It must be emphasized that the repair work for the temporary operation of the plant and the operation itself did not significantly affect the scheduled date to finish all the bypass works for normal operation of the plant, since the works were carried out in parallel with the excavation of the bypass tunnel.

The pipes were 4.50 m long, resting each one on two steel prefabricated supports. The supports were anchored to the concrete lining with steel bolts. Furthermore, they were equipped with openings in their bottom to let the infiltrating water enter the drainage system. The pipes were fixed to the steel supports by means of a special rubber band provided with a steel adjustment band and bolts, as shown in Figure 6.

Figure 6. Mounting and adjusting of GRP pipe on steel supports

The pipes were transported into the affected tunnel stretch through the access gallery to the valve chamber of the plant and through the valve chamber itself. Previously, CELEC dismounted the 2.40 m diameter butterfly valve and cut and dismounted the piece of exposed steel pipe, upstream of the valve, between the tunnel and the valve.

Trucks transported the pipes to the valve chamber, where they were introduced into the tunnel by means of the chamber bridge crane, . A special steel platform on wheels transported the pipes on two rails to the site, where a rail hanging from the roof allowed the tubes to be transported to the installation site (Figure 7). This transportation solution was chosen since there was only limited free space between the tunnel and the pipe available. In order to allow the installation of a small walking platform, on one side of the pipes, to facilitate the inspection or reparation work, the pipes were fixed eccentrically to the tunnel axis.

Figure 7. Transportation of pipes to the installation site

The pipe installation was performed from upstream to downstream. Therefore, it was necessary to first build the upstream temporary concrete plug around the first piece of pipe. Also, the prefabricated steel supports were previously anchored to the concrete lining.

Once the connection between pipes was realized the water tightness of the O-ring (Figure 8) seals was inspected to detect any leakage and subsequently implement proper counter measures, if required.

Finally, the downstream temporary concrete plug was built around the last piece of the GRP pipe.

Figure 8. Connection between pipes and the water tightness of the O-ring

At the time of writing this paper, the excavation of the bypass was suspended close to the two temporary concrete plugs, leaving a natural rock mass of about 35 m at each connection with the undamaged headrace tunnel. It is expected to work as a natural plug and to avoid the risk of water leakage to the bypass tunnel.

The concrete lining work in the excavated bypass tunnel is in progress while presently one turbine is temporarily operating. According to the contractual schedule, the delayed excavation work for the junctions between the existing damaged tunnel and the bypass tunnel will resume in summer 2013. The excavation will then connect the bypass tunnel with the existing undamaged tunnel. The affected tunnel will then be isolated from the bypass tunnel by means of two concrete plugs provided at its ends, next to the east (EE) and to the west (EO) connection points. During this process, the temporary operation of the plant will be halted.

After construction of the access tunnel plug equipped with a watertight inspection door, all works to put the plant in normal operation again are expected to be finished. The plant is expected to restart its normal operation in autumn 2013.

7 Conclusions

Immediate actions are important to overcome natural disasters that affect a power plant.

Field research and design work carried out on in parallel with the execution of reparation work allowed the project to save time and reduce costs related with the closure of the plant.

The temporary operation of one turbine let the plant reduce the economic losses caused by the lack of power generation and by the unutilized spilling water of the reservoir.

The solution implemented in this case did not affect the contractual working chronogram required to put the plant back into normal operation.

Having a common objective was a key element that allowed the stakeholders of the project (owner, engineers, contractor, supervisors) to overcome a critical problem, in the least amount of time and at a reasonable cost.

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