Technical Description of Design and Construction Aspects of Three Underground Caverns for Hydroelectric Projects in Colombia, South America

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1. Design and Bidding Processes in Porce II, Porce III and Porce IV Hydroelectric Projects

The design processes of the underground works were carried basically by Colombian consultants with the revisions and recommendations of expert independent consultants. The designs took place from the exploratory campaigns with borehole drillings, construction of exploratory galleries, excavation of trenches, and the testing of rock samples in labs, among others. Later the consultants used all the geological and geotechnical information in order to draw the bid plans and to write the technical specifications. The owner integrated all the technical and legal information and, with the collaboration of the consultants, opened the bidding processes for the works. A similar procedure is being followed during these days for Porce IV underground works design and bidding. It is important to say that Porce II and Porce III hydroelectric projects were partially financed by the Inter-American Development Bank (IADB), so the bid regulations for Porce II and Porce III underground works took many rules and forms from the IADB.

The bidding processes of the Porce II and Porce III hydroelectric projects were very complex due to the legal regulations in Colombia in relation with the Power business, which is regulated by the government and due that the owner is a public utility. However, for Porce II underground construction works 14 proposals were received from contractors of Brazil, Colombia, France, Italy, Spain, among others, in May 1994. This contract was awarded to an Italian – Colombian consortium for US$ 54 million. Afterwards, the works were finished by a Spanish – Colombian consortium, which was awarded the ending of dam and underground powerhouse for US$ 80 million in July 1999. For Porce III underground construction works, three proposals were received from contractors of Brazil, Colombia and Spain, in April 2005. This contract was awarded to a Brazilian – Colombian consortium for US$ 208 million of such date. It is important to take into account the magnitude and differences between the underground works awarded in Porce II and Porce III, which will be described ahead in this article.

2. Geographical Location of the Porce II, Porce III and Porce IV Hydroelectric Projects

Figure 1 shows the general location of the Porce II, Porce III and Porce IV hydroelectric projects. Porce II is located 120 km northeast of Medellín, Colombia; Porce III, 147 km; and Porce IV, 200 km; all of them using the same roadway from Medellín.
Figure 1. General location of the Porce II, Porce III and Porce IV hydroelectric projects, all of them owned by Empresas Públicas de Medellín E.S.P.

3. General Description of the Powerhouse and Underground Works of Porce II Hydroelectric Project

Figure 2 shows an isometric view of the main underground works of Porce II Hydroelectric Project.

Figure 2. Isometric view of the main underground works of Porce II Hydroelectric Project
The powerhouse excavation lasted about 12 months since February 1996 to January 1997. The main geology of the most important works was composed by metamorphic rocks (hornfels) and igneous rocks (quartzdiorites). In general terms the rock was very competent; the rock faults were of small width, about 1 m, with filling of crushed materials and these faults did not affect the general stability of the caverns.

4. General Description of the Powerhouse and Underground Works of Porce III Hydroelectric Project

Figure 3 shows an isometric view of the main underground works of Porce III Hydroelectric Project.

![Isometric view of the main underground works of Porce III Hydroelectric Project.](image)

The powerhouse excavation lasted about 12 months since December 2006 to December 2007. The main geology of the most important works was composed by metamorphic rocks (schists and gneisses). In general terms, the rock was very competent, four discontinuity systems were found (one was foliation and the other three were fractures). Several foliation fault zones were detected with fillings of medium to soft consistency. The maximum width of these faults was 1 m. Once the Porce III hydroelectric Project is concluded, the underground infrastructure of Empresas Públicas de Medellín E.S.P. will have about 100 km of tunnels and five underground powerhouses.

5. General Description of the Powerhouse and Underground Works of Porce IV Hydroelectric Project

Figure 4 shows a scheme of the main underground works of Porce IV hydroelectric project. The powerhouse excavation is scheduled to last about 12 months beginning in the first quarter of
The main geology of the most important works is composed by metamorphic rocks (gneisses).

Figure 4. Schematic view of the main underground works of Porce IV Hydroelectric Project.

6. Porce II Caverns and Additional Works

6.1. In Situ Stresses Investigations

According to the overcoring tests made in the powerhouse area from the exploratory galleries, the vertical stress in hornfels was 6.53 MPa was concluded. The main horizontal stresses, longitudinal and transversal in relation with the caverns axis were 7.94 MPa and 8.71 MPa, which mean a ratio between horizontal and vertical stresses of 1.22 and 1.33 respectively. Similarly, in a place where 85% of data were in quartzdiorite, the vertical stress was 5.73 MPa was concluded. The main horizontal stresses, longitudinal and transversal in relation with the caverns axis were 4.21 MPa and 5.30 MPa, which mean a ratio between horizontal and vertical stresses of 1.57 and 1.38 respectively. Although these tests showed some low correlation factors of data, they showed some consistencies taking into account the results obtained by hydrojacking tests. According to the results, the major principal stress was parallel to the land surface, while the minor principal stress was perpendicular to the land surface. The stress magnitudes showed correlation with the depths in the sites. The magnitude of hydraulic head at the headrace tunnel was of 250 m or 2,50 MPa, in comparison with an approximate geostatic stress of 6,30 MPa, this last being 2,50 times greater than the hydraulic head.

6.2. Excavation Procedure

The excavation sequence of the powerhouse included the excavation of 4 and 6 m high benches, leaving 2 m in the walls perimeter, which were excavated later by smooth blasting. Once excavated a bench, 120 KN bolts of 5 to 7.5 m of length, and two 5 cm thick shotcrete layers with a steel mesh between them were installed. By means of the lower construction tunnel, two pilot
tunnels located in the walls of the cavern were excavated in order to facilitate the excavation of the lower benches; in the downstream surge tank cavern, a lower tunnel with the same purpose was excavated. See Figure 5.

Figure 5. Porce II Powerhouse Cavern Excavation Sequence

6.2.1. Most Important Aspects During Construction

Some special events in the caverns construction are detailed as follows. Some rock wedge loosening in the north and in the west rock walls of the powerhouse were presented, which were treated by the installation of additional rock support, such as rock bolts, and the installation of additional instrumentation. The magnitude of the wedges were of 27000 kg and 22000 kg, respectively. Another event was the cracking of shotcrete in the access tunnel area near the powerhouse; it was necessary to install systematic bolting in the roof and in the floor of the access tunnel. In all cases the measurements registered by the instrumentation were stabilized after a time. The deformation predicted by design studies were of about 10 mm. During construction were measured deformations of about 14 mm, but these last did not affect the general stability of the caverns.

6.2.2. Instrumentation

A total of 88 extensometers were installed, 27 of multiple position and 61 of only one position; 41 instruments were installed in the powerhouse cavern, 37 in the downstream surge cavern, 4 in the transformers cavern and 6 in the draft tunnels. Although the rock movements measured were bigger than expected, the rock performance was normal during excavation and support.

6.3. Additional Important Works

6.3.1. Headrace Tunnel

This tunnel was excavated by drill and blast, 73 % was excavated in quartzdiorite and 27 % in hornfels. The average tunnel overburden was 250 m. The final lengths of types of rock excavated in the headrace tunnel are summarized as follows: Very good rock without many fractures: 2152 m, equivalent to 48,78 %; Good rock with fractures: 737 m, equivalent to 16,70 %; Regularly
fractured rock: 468 m, equivalent to 10.60 %; Very fractured rock: 1035 m, equivalent to 23.45 %; Fault zones: 20 m, equivalent to 0.45 %. The final linings in the tunnel were as follows: Shotcrete in different thicknesses depending on the cross section specified: 84.6 %; and full cross section hydraulic concrete, with different density of reinforcement: 15.4 %.

6.3.2. Tailrace Tunnel

During the tailrace tunnel excavation exploratory boreholes were drilled in order to check the rock overburden. One of them registered a water inflow of about 2.75 l/s with a pressure of 0.35 MPa; the water inflow lowered with time to 0.15 l/s. This water occurrence was possibly due to the near vicinity of the Porce river.

7. Porce III Caverns and Additional Works

7.1. In Situ Stresses Investigations

According to the overcoring tests made in the powerhouse area from an exploratory gallery, in one of the test sites (Number 2), the K ratio between horizontal and vertical stresses was of 1.83 corresponding to a horizontal stress of 16.07 MPa and a vertical stress of 8.76 MPa was concluded. The least value of the minor principal stress measured was of 3.92 MPa in Number 3 test site; the magnitude of this stress is similar to the magnitude obtained by the hydrojacking tests made nearby. The general geology of the tests was in gneiss. Although some tests showed low correlation factors of the data, the Number 2 site showed a correlation factor of 0.92, which was acceptable. The magnitude of hydraulic head at the headrace tunnel was of 350 m or 3.50 MPa, in comparison with an approximate geostatic stress of 9.0 MPa, this last being 2.60 times greater than the hydraulic head.

7.2. Excavation Procedure

The next diagram shows the excavation stages and production rates of excavation in the main cavern. See Figure 6.

Figure 6. Porce III Powerhouse Cavern Excavation Sequence
The caverns support was installed in a systematic way and consisted in a 5 cm shotcrete layer plus a wire mesh, rock bolts and an additional 5 cm shotcrete layer. The rockbolts varied from 5 m to 7 m long in an approximate 1.5 m by 1.5 m square arrangement in the powerhouse. In the transformers cavern the rockbolts were 4 m long in an approximate square arrangement of 2 m by 2 m.

7.2.1. Most Important Aspects During Construction

Some special events in the caverns construction are detailed as follows. Several loosening rock blocks were presented, which were supported by rock bolting. In the west wall of the powerhouse, an increase in the cross section of the busbar galleries which connect the powerhouse cavern to the transformers cavern was necessary, consequently, the rock pillars between the busbar galleries and the manifold tunnels located below were diminished. Additionally, some rock discontinuities which allowed the loosening of a rock mass were presented. One of the extensometers installed in the area registered a maximum deformation of 26.95 mm. (The design deformation prediction was 5.9 mm). Afterwards, when the powerhouse bench between elevations 315.5 and 311.5 was excavated, a cracking appeared in the shotcrete installed in the arch roof between abscissas 42 and 75. The cracking of the shotcrete was attributed to several causes or to a combination of them, such as: rock stresses redistribution; rock – shotcrete low adherence; the preliminary excavation of a gallery in the arch during the design investigations; among others; the maximum deformations in the powerhouse roof cavern varied between 5 and 17 mm (the design deformation prediction was 4.6 mm with the cavern completely excavated). After the total excavation of the powerhouse cavern, the deformations in the arch rock have been zero.

7.3.2. Instrumentation

A total of seven instrumentation stations were installed, with a total of 81 extensometers of four positions installed. Some extensometers registered deformations bigger than estimated, with a maximum value of 29.4 mm. These deformations were controlled by installation of additional rock support, such as rock bolts and shotcrete. Currently the deformation rate is zero.

7.4. Additional Important Works

7.4.1. Headrace Tunnel

This tunnel was excavated by drill and blast, about 50 % was excavated in schists and about 50 % in gneiss. The average tunnel overburden was 270 m. The final lengths of types of rock excavated in the headrace tunnel are summarized as follows: Type I: Very good rock: 7240.60 m, equivalent to 58.50 %; Type II: Regular rock: 4914.60 m, equivalent to 39.70 %; Type III: Bad rock: 213.50 m, equivalent to 1.80 %. The final linings in the tunnel were as follows: Shotcrete in different thicknesses and rock without any support: 70.60 %; full cross section hydraulic concrete, with different density of reinforcement: 29.40 %. In general terms, the tunnel was excavated without big problems. The only aspect to remark was the presence of underground water in the headrace tunnel downstream of the intersection with the adit No. 2, averaging about 150 l/s. The contractor had to pump the water because he was working from upstream to downstream, but this cost was paid by the owner according to the contract specifications.
8. Porce IV Caverns and Appurtenant Works

Taking into account the technical and contractual experiences during Porce II and Porce III underground construction contracts, some aspects to improve the Porce IV Hydroelectric Project performance appear, such as the design of realistic excavation and supporting procedures; design of bid packages in order to optimize the construction’s period of the project; design of extensive field investigations in order to reduce the construction risk of the project; among others. According to the above, the first package bid of Porce IV main works will mainly contain: construction of the diversion tunnel; excavations for the right abutment plinth in the dam site; construction of the access tunnel and some galleries to the powerhouse cavern. This bid is expected to be opened in the first semester of 2010, in order to begin works at the end of 2010. The bids corresponding to finishing the dam and underground works are scheduled to be opened in the first quarter of 2011.

9. Conclusions

From the experiences during the Porce II and Porce III underground works construction, the geology in Porce II was better than in Porce III can be concluded. The Porce III powerhouse showed more deformations and required more rock support in some special cases than in the Porce II powerhouse cavern. The percentages of excavation of the headraces in different rock types varied in both projects, but Porce II showed a better rock performance by comparing the percentages of type of rock excavated and the percentages of final linings used. The performance of the contractors in the Porce II and Porce III powerhouse excavations is very consistent, both caverns were very similar in volume of rock excavated and in complexity and both caverns construction lasted about the same, 12 months. The rock deformations investigations in design for both projects were surpassed by the real situations during construction, so the investigations gave an order of magnitude of deformations, but they were larger than predicted in general terms.

References:


