

Rock Engineering Aspects of the Cheves Hydropower Project Powerhouse and Transformer Caverns

Author: José Miguel GALERA, Subterra Ingeniería, S.L., Spain, jmgalera@subterra-ing.com

Co-author: Hans ANDERSSON, Constructora Cheves, SAC (joint venture Hochtief Solutions AG, SalfaCorp SA and ICCGSA), Peru, handersson@cch.com.pe

Topic: Developments in Use of Underground Space: Case Studies (Traffic, Waste, Energy, Water, Sewer, Flood Protection, Commercial and other Uses)

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Summary: *The Powerhouse and Transformer caverns at the Cheves Hydropower Project was excavated in relatively hard igneous rock. The geology in the area of the powerhouse proved to be structurally complex given the presence of faulting and almost horizontal parallel shearing planes. Careful consideration had to be given to aspects such as in situ stresses, rockmass strength and deformation characteristics.*

1. Introduction

The Cheves hydropower project is located on Huaura River and Checras River, in the Andes Mountains of Peru (see Fig. 1).

The Project is composed of three small dams and the underground works dominate the infrastructure, having a total of approximately 19 km of tunnels:



Fig. 1 Cheves Hydropower Project location

- The **transfer tunnel**, between the Huaura Intake and the Checras reservoir presents a length of 2,580 m.
- The **headrace tunnel** have a 9.693 m long (22.6 m² and 30.1 m² cross section), which has an upper section at a grade of two per cent and a lower section at 14 per cent grade. At the junctions of the lower and upper tunnels will be a surge tunnel of approximately 700 m long, also with a 14 per cent slope.
- The end of the headrace tunnel splits into two short penstock tubes, taking the flow to the generating units in the **powerhouse cavern** (60 m long by 32 m high by 15.5 m wide). The transformer cavern (27.5 m long by 14 m high by 11.2 m wide) is immediately adjacent, and a large access tunnel reaches both.
- Downstream, the flow is discharged into the 3.312 m long (24.9 m² cross section) **tailrace tunnel**.

The powerhouse and transformer caverns at the Cheves Hydropower Project have been excavated in relatively hard rocks. The geology in the area of the caverns proved to be structurally complex given the presence of major tonalites intrusions with associated sub-horizontal shear joints.

Careful consideration was given to aspects such as in situ stresses, rockmass strength.

2. Geometrical characteristics

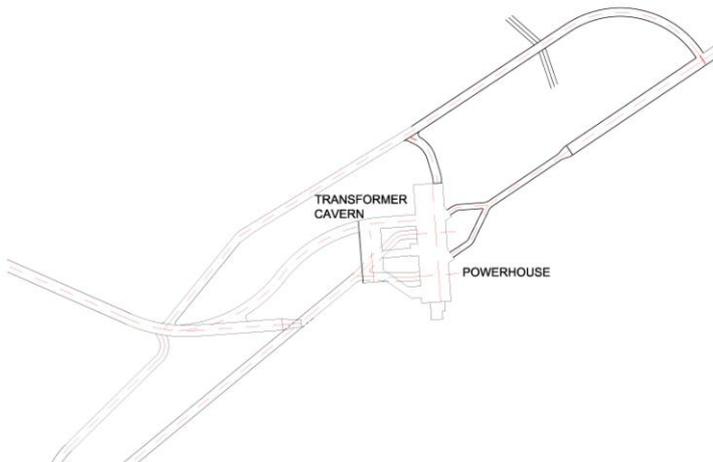


Fig. 2 Powerhouse and transformer caverns layout

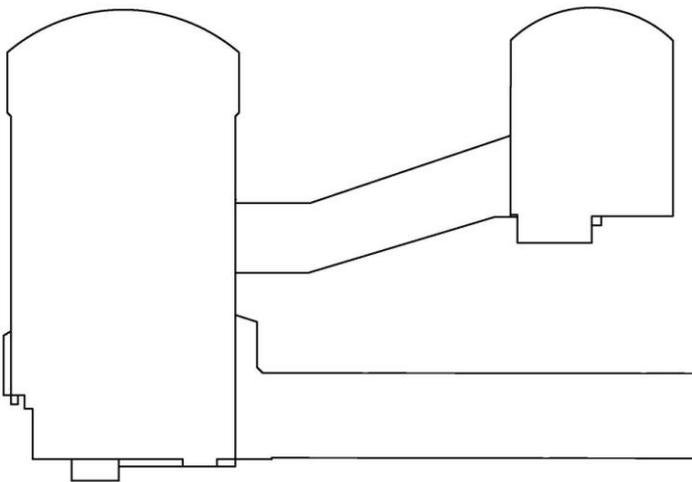


Fig. 3 Powerhouse and transformer cavern scheme

3. Engineer Geology aspects

3.1 Geology

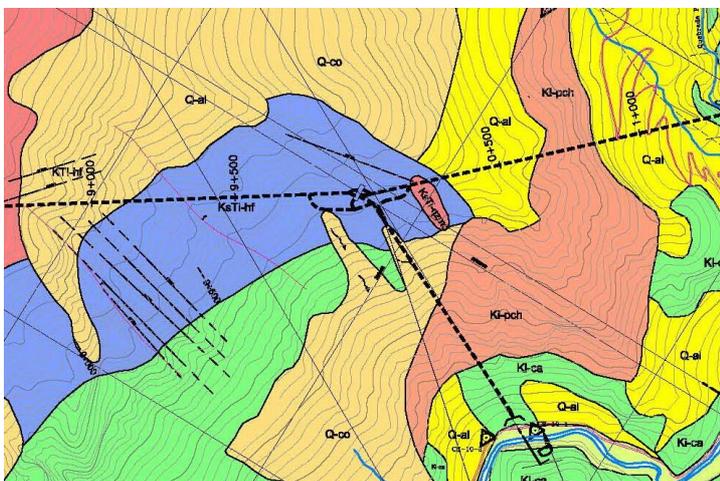


Fig. 4 Geological Map.
 (KI-pch Churin Bajo Stock, KI-Ti-Hf Hornfels Unit)

The power station is located in the mountain formations on the left side of the Huaura River about 1.5 km upstream of the Paccho creek - Huaura River confluence.

The powerhouse complex consists of the main cavern with two Pelton turbines and a transformer cavern arranged in parallel with the main cavern, containing two main transformers. The access to the powerhouse complex is via the 960 m long access tunnel.

The powerhouse cavern presents the following dimensions: 31.5 m height, 72 m long and 16 m width. The transformer cavern presents the following dimensions: 16 m height, 28 m long and 11.2 m width. Distance between caverns is 19 m. Overburden is about 850 m.

Traditionally, the most common shapes for the design of a hydropower project cavern are: trapezoidal, mushroom, circular shape, bullet shape and horse shoe. The hydropower caverns at the Cheves Project present a slightly planar roof which gives a near rectangular shape. (see Fig. 2 and 3).

The Cheves Hydropower Project is located in the Huaura Basin. The Geology is complex with sedimentary, volcanic, igneous and metamorphic formations across the project.

The Region is near the Nazca plate and consequently is under active tectonic. Risk of earthquakes is moderated in the project area.

The Powerhouse and transformer cavern area was mainly affected by the Churin Bajo Stock group consists in intrusive rocks with tonalite / quartz-monzonite composition.

The geological frame is shown in Fig. 4.

3.2 Intact Rock Properties

The Powerhouse and transformer cavern area was mainly affected by the Churin Bajo Stock group consists in intrusive rocks with tonalite / quartz-monzonite composition. This tonalite is dark grey with a crystalline texture and medium to fine grain size.

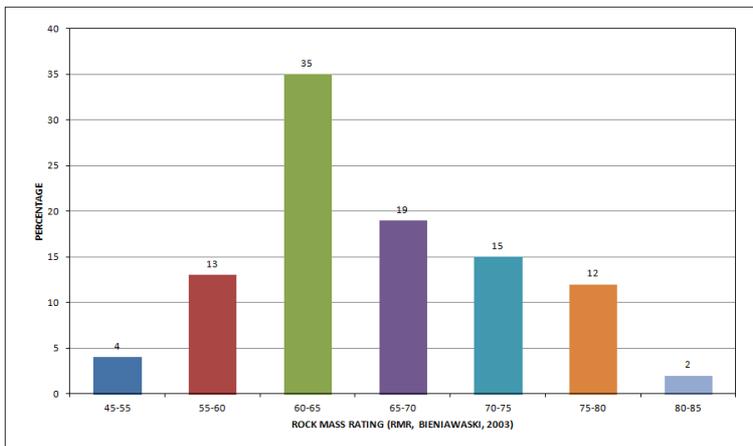
In general they show a high strength, low to moderately weathered in the surface, showing thin coats of iron oxides in fractures, which are persistent.

These tonalites are fresh, and show high UCS values between 125 and 185 MPa. Any water presence was noticed during the excavation.

The recommended values for design purposes are the following:

- Uniaxial compressive strength = 140 MPa
- $m_i = 25$
- Modulus ratio MR = 450

3.3 Rock Mass Quality

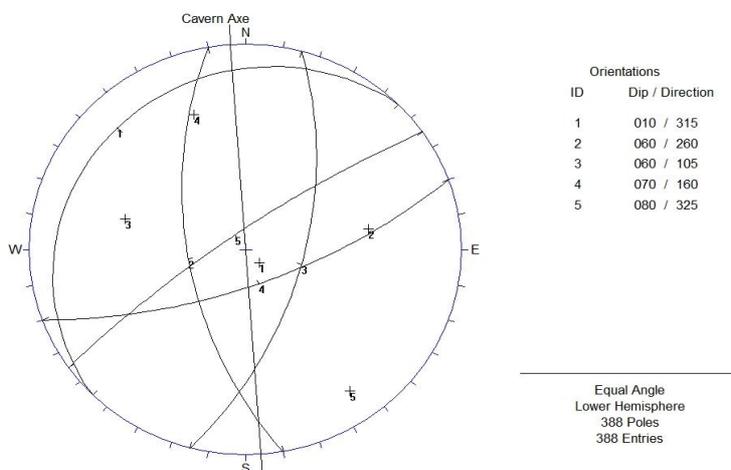


During the excavation of the powerhouse and transformer cavern a detailed face mapping inspection was carried out. As a result an assessment of the rock mass quality (RMR system) as well as a detailed joint characterization was done.

In relation with the rock mass quality, Fig. 5 shows the RMR statistical distribution.

Fig. 5 RMR distribution at the Power house top heading.

3.4 Structural Conditions



Also a detailed structural mapping of the powerhouse and transformer cavern was done.

Those data were analyzed using Dips software to determine orientations of the major planes of the existing joint sets (see Fig. 6). The statistical analysis of the joint system observed indicated the presence of 5 joint sets.

One sub-horizontal joint system associated to shear planes, two sub-vertical joint sets parallel to the long walls and two joint sets perpendicular to the long wall and dipping inside the caverns.

Fig. 6 Joints sets derived from the discontinuity analysis.

Finally the joint conditions (spacing, continuity, roughness, aperture and infilling) was analyzed. The average spacing was 20 cm (5 joints per meter), the continuity was in the range 3 – 10 m, the aperture ranges from 1 to 5 mm with smooth fillings, the roughness was medium and the weathering is low.

3.5 Natural In situ stress

Initially the natural stress field assumed was derived from regional information as well as from the tectonic frame. It was considered an unfavorable scenario with the following ratio between horizontal and vertical stresses: $K_{0h}=1.0$ (with a strike N150°E) and $K_{0H}=1.5$ (with a strike of N-60°E).

As this stress frame is a key matter for design purposes, three different site investigations was conducted. The first one using overcoring techniques and the two lasts using hydrofract stress measurements.

The measurements using overcoring consisted in five measurements. The magnitudes of the maximum principal stress σ_1 ranged between 18.6 to 59.8 MPa. According to the mean value the resulting relation between horizontal and vertical stresses would be around 1.2 and an orientation quite similar to the one obtained by geological estimations (N-45°E), but the scatter of the results was relatively high.

For this reason two different site measurements using hydro-fracturing were decided. In both cases the magnitudes obtained were similar, with relatively low values of horizontal stresses. Consequently the natural stress filed was defined as follows:

$$\begin{aligned}\sigma_v &\text{ between } 21.7 \text{ and } 22.1 \text{ MPa} \\ \sigma_h &\text{ between } 12.8 \text{ and } 13.7 \text{ MPa } (K_{0h}=0.62) \\ \sigma_H &\text{ between } 20.3 \text{ and } 21.3 \text{ MPa } (K_{0H}=0.96)\end{aligned}$$

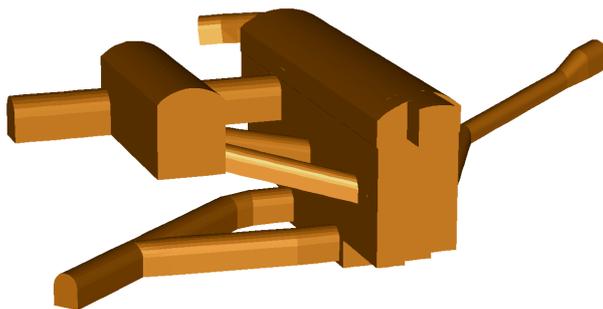
The orientation of the maximum horizontal stress was N95°E.

4. 3D Stress Modellization of the Powerhouse Complex

A computer based 3-dimensional stress analysis of Powerhouse Complex of Cheves Project has been carried out using RocScience software "Examine3D 4.0".

Examine 3-D is a three-dimensional boundary element method and is appropriate for preliminary elastic analysis of a problem in which the three dimensional geometry of the openings is important. In this three-dimensional analysis, the stress concentrations and the influence of the three dimensional geometry are clearly indicated.

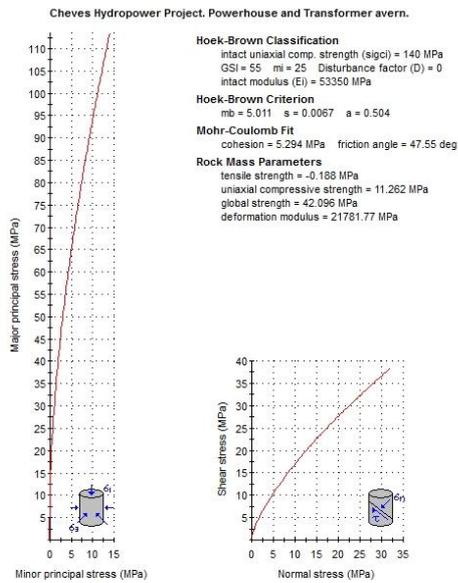
This software is based on Boundary Elements Method (BEM) and allows carrying out a wide range of three-dimensional underground analyses, providing stresses and displacements around the excavations as well as the strength factors equivalent to safety factor of the rock mass, considering the induced stresses versus the rock mass strength.



The Examine 3-D model of Powerhouse Complex used for the analysis is shown in Fig. 7. The model consists of total 14586 elements and 7171 nodes. The elements are triangular and the displacements vary linearly over the surface of elements.

Fig. 7 Examine 3-D model of the Powerhouse Complex.

4.1 Input Parameters in the 3-D BEM analysis



Field stresses were measured by Hydro fracture tests as mentioned below. Overburden in the Powerhouse is 850 m.

The elastic moduli for the rock mass (E_{rm}) has been estimated by Galera & Bieniawski (2006) expression, while the strength parameters have been estimated using RocLab software (see Fig. 8).

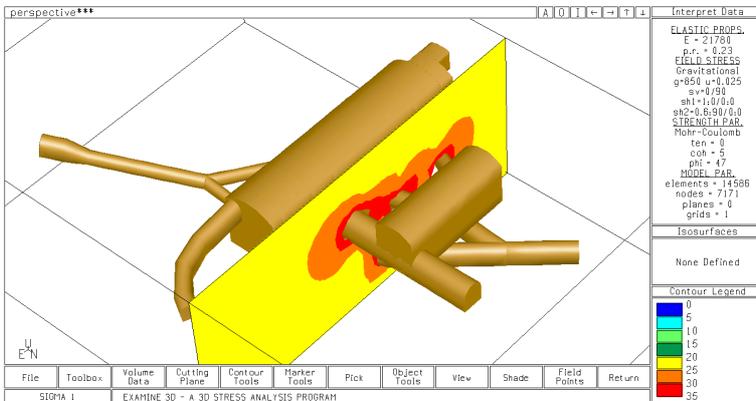
'D' is taken zero in this case and values for m_i (=25 for tonalites) and GSI (=55 for tonalites) have been taken. Other parameters e.g. Poisson's ratio is estimated by the Karzulovic (1999) equation.

Fig. 8 Analysis of Rock Strength using RocLab

4.2 Analyses results and Interpretation

Following the main results obtained are presented.

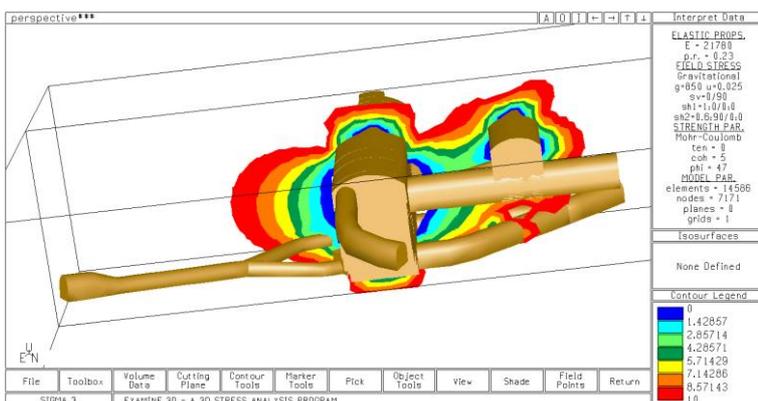
4.2.1 Displacements



The maximum displacements are in the wall of the main cavern with maximum values lesser than 3 cm. The rest of the displacements have values below 1.2 cm, decreasing as they are located further away from the area of influence of the main cavern.

Fig. 9 Maximum principal stress

4.2.2 Principal stresses



The principal stress distribution is shown in Fig. 9. As it can be observed there is an area around the bus ducts between both caverns, where the main stress rises in comparison with other places in which the annexed tunnels are further. This stress increment rises from 25 to 35 MPa, representing an increment of the main stress of 40% over the initial natural stress at the same location.

Fig. 10 Minimum principal

Fig. 10 shows the minimum principal stress, where an appreciable decompression is noticed; with values ranging from 21 MPa to values in the range of 3-6 MPa.

4.2.3 Safety factor

The safety factor's iso-surfaces of 1.0 and 1.2 has been analyzed (see Fig. 11 and 12).

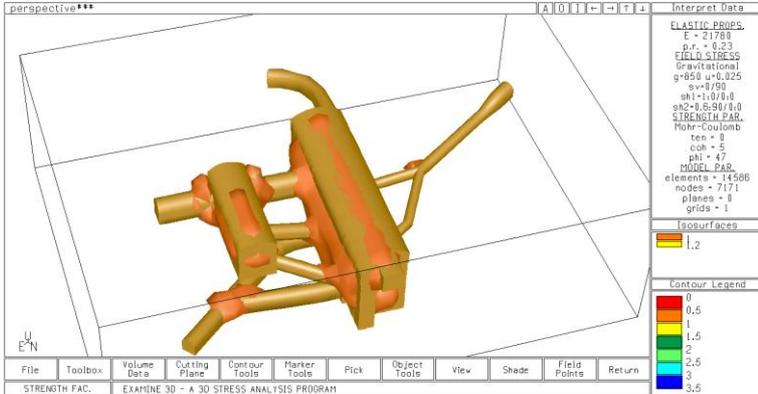


Fig. 11 Isosurface of the Safety Factor 1.0.

The first one would indicate approximately the area of plastification around the excavations. This shows a plastification in the contour of the opposite walls of the caverns about 4 m deep, while the massif located between the two caverns will increase its plastification up to 1.5 meters on each wall, reducing the central block to an elastic ground range of 4 to 5 meters width.

In any case the plastification around the excavation is moderate according to the results.

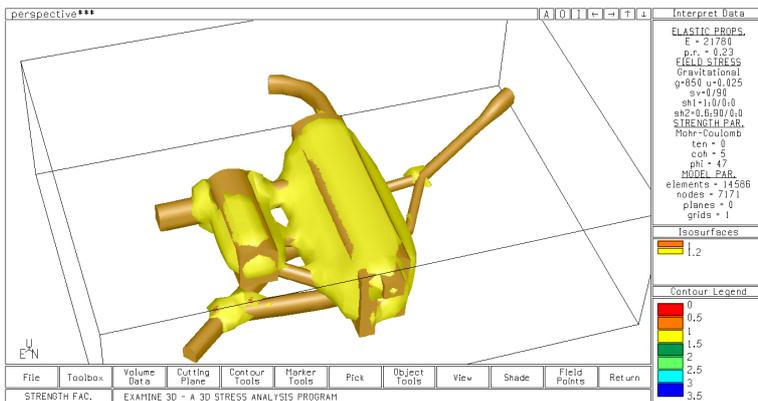


Fig. 12 Isosurface of the Safety Factor 1.2.

5. Construction sequence

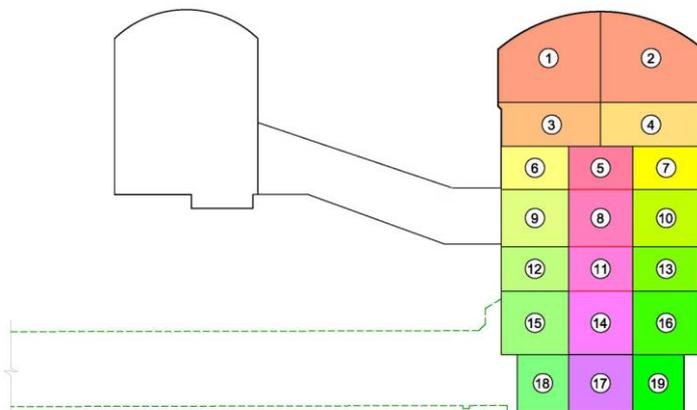


Fig. 13 Powerhouse Excavation Sequence

The excavation of the Powerhouse started on January 2012 and finished on June 2013.

The excavation was executed with conventional methods, drill & blast, following a bench sequence (see Fig. 13).

The excavation process was in general executed from the upper towards the lower levels, with the limits of each excavation level being influenced by adjacent connection tunnels as given in the design.

subsections executed from top to bottom and approached from the different access routes depending on their entry point within the caverns.

Excavation works in the Powerhouse have been divided into different



Fig. 14 Powerhouse excavation. Bench I (Crown)

Showing individual excavation steps with corresponding level heights. From top to bottom Powerhouse it was subdivided into:

Top Heading (1.580m - 1.572,85m) - 7.15m
Bench 1 & 11 (1.572,85m - 1.566) - 6.85m
Bench 111 (1.566m - 1.561,7m) - 4,30m
Bench IV (1.561,7m - 1.557,65m)- 4.05m
Bench V (1.557,65m - 1.553,2m)- 4.45m
Basement (1.553,20m- 1.548,5m)- 4,70m

Also a muck hole was executed connecting bus duct with tailrace in order to facilitate the mucking of the excavation.



Fig. 15 Transformer Cavern Excavation

Fig. 14 and 15 show the aspect of the Powerhouse excavation at Bench I and the aspect of the Transformer Cavern.

The Transformer chamber was excavated between March 2012 and November 2013. The excavation was executed from the access tunnel.

The excavation sequence was subdivided in a inclined access tunnel excavation, top heading excavation and the corresponding bench excavation.

Fig. 16 and 17 show the aspect of the Powerhouse at Bench VI, and once finished.

6. Support and monitoring

The support of the Powerhouse was based in the combination of short and long bolts with a double layer of shotcrete that includes welded wire mesh in between of the layers of shotcrete.

After each advancing blast an inspection of the rock surface was made by geologist and engineer geologist. Geological and geotechnical data were collected of every face, including a rock mass classification using both methods RMR (Bieniawski, 2003) and Q-System (Barton, 2002).

The excavation was continuously monitoring with a total of 33 convergence stations, that combine survey measures and extensométrica tape measures.

Additionally, 9 extensometers were installed in the walls and crown of the Powerhouse. Lengths of the extensometers vary from 9 to 20 m.



Fig. 16 Powerhouse Excavation. Bench VI

The support of the Transformer cavern was also defined in the use of bolts, in this case the length of the bolts was the same in all the walls (6 m).

A double layer of shotcrete with mesh was also installed.

Transformer cavern was monitored with convergence stations, 4 were installed for the extensometer tape and 9 were monitored with survey equipments.



Fig. 17 Powerhouse Excavation. Finished.

7. Conclusions

Powerhouse and transformer cavern of the Cheves Hydropower Project were excavated in igneous rock (tonalites), moderated to low jointed Rockmass was encountered.

Natural in situ stress was anisotropic; this factor was considered fundamental for the design of the excavations and supports.

Rock Engineering aspects are fundamental in the design of Powerhouse and Transformer Caverns. Excavation shape, tunnels layout, rock mass conditions and geologic structural behaviors have to be considered.

Natural in situ stress is specially needed to be analyzed in areas under active tectonic.

Acknowledgements

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