# METHODOLOGICAL ASPECTS OF 3D NUMERICAL ANALYSIS ON CAVERN COMPLEX IN DIFFICULT CONDITIONS

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**ABSTRACT.** In recent years there has been a remarkable development of methodologies and calculation tools to assist designers of underground projects to adopt more effective and conscious solutions. Major works such as hydroelectric plants, especially because of their strategic importance, certainly fall within the spectrum of application of these tools. This article aims to present the most relevant aspects in the geomechanical analysis of a cavern complex belonging to a hydroelectric repumping plant with a power of 344 MW. The critical issues related to this project are mainly given by the anisotropy of the in-situ stress state in which the cavern complex is located, by the complex geological conditions and by the large dimensions of the excavations. After an introduction on the characteristics of the works and a framework of the geological and geomechanical context, the solutions adopted for the pre-dimensioning of the support systems are illustrated, as well as the calculation results obtained with a careful and comprehensive numerical modelling.

## 1. INTRODUCTION AND GENERAL ASPECTS

The main components that constitute the central part of the generation circuit (Figure 1) are: 1. Powerhouse (PH, cavern housing turbines which size is about 50m (H) × 18m (W) × 92m (L) where water is conveyed into turbines to convert kinetic energy into electrical energy); 2. Transformer Hall (TFH, which size is about 20m (H) ×15m (W) ×76m (L) where voltage and electric power are varied). The system also includes a series of tunnels connecting the main caverns and access/construction tunnels: 1. Busbar tunnels 1 and 2 (BST1 and BST2); 2. Main Access Tunnel (MAT); 3. Pilot tunnels 1 and 2 (respectively connected to the northern wall of the Powerhouse (PT1) and of the Transformer Hall (PT2); 4. Secondary access tunnels (Adits). It is important to remark that during the excavation of the pilot tunnels an important fault system was identified in the north side of the complex: this fact caused the decision to change the design by rotating the entire complex of about 30°. At that stage however the excavation of the main access tunnel was already performed, which was then subsequently filled with concrete (OLD MAT).

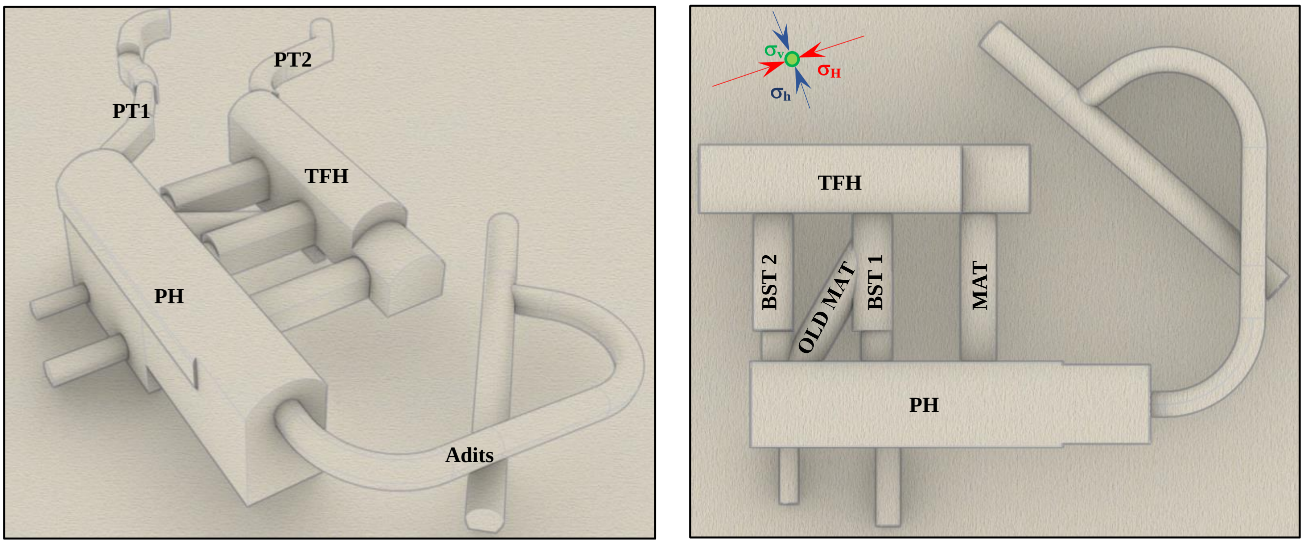



*Figure 1. Perspective view (left) and from top (right) of the cavern complex.*

The excavation of the caverns is carried out with successive stages of variable height (from 4 to 8 m) depending on the conditions of the rock mass and mainly with the *Drill & Blast* method (when the conditions do not allow the use of this technique, traditional excavators are used). PH and TFH are conventional horseshoe shaped caverns with vertical sidewalls, so the shape of the vault helps to optimally distribute the acting stresses.

## 2. GEOLOGICAL AND GEOMECHANICAL CONTEXT

The geological context is characterized by a competent basaltic matrix (*Bs-strong*), fractured basalt (*Bs-weak*), inclined layers of pyroclastic material (*Pyr*) and fault systems. From boreholes data and surveys on excavation exposed faces it was generated using the dedicated tool *Leapfrog Works*® a three-dimensional geological model (Figure 2). This type of software uses an implicit geological modeling method generated by algorithms starting from different combinations of different types of data.

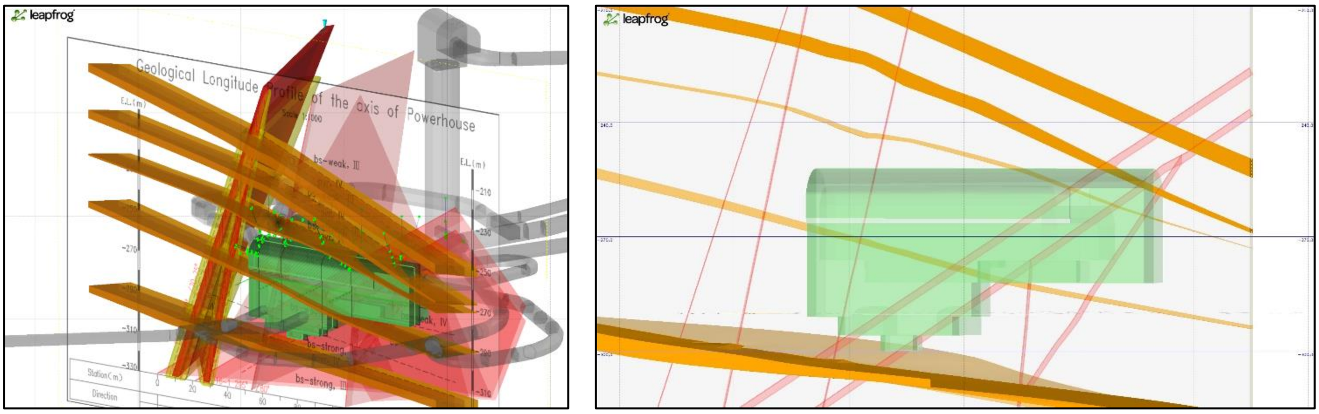



*Figure 2. Results of 3D geological modeling (left) and focus on PH (right).*

The geological information deriving from the three-dimensional geological analysis is subsequently managed from the geometric point of view by a 3D modelling code (Figure 3-left), to be finally properly imported into the finite element analysis code $RS^3$ (FEM - Figure 3-center). At the same time the excavation phases to be simulated are defined (through the removal of groups of elements previously defined): after the initialization of the constant stress state representative of the deep conditions, initially the excavation of PT and OLD MAT is simulated, then the excavation proceed with the TFH in three phases, the first two phases of PH in three slices, the BST excavation in a single phase and lastly the last portion of PH in three phases as shown in Figure 3-right.

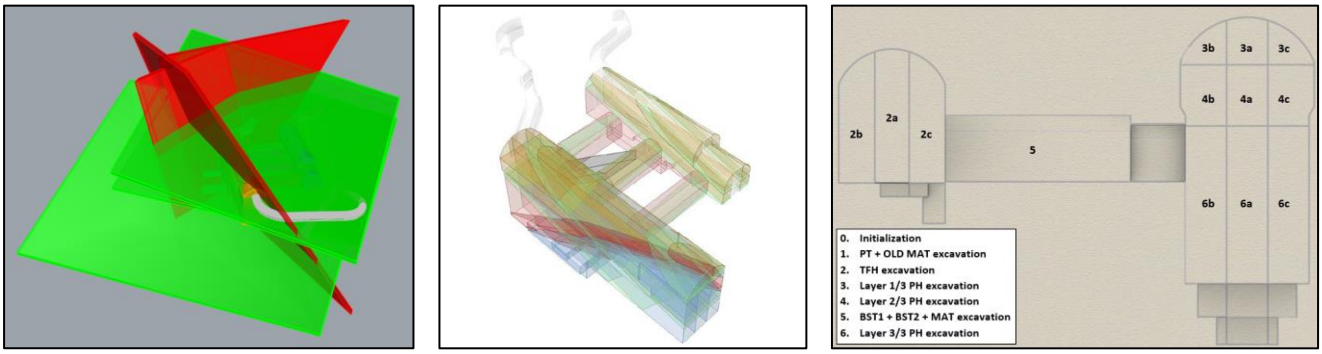



*Figure 3. 3D representation of fault systems (in red) and pyroclastic layers (in green) around the cavern complex (left), lithologies on excavation zones in $RS^3$ (center) and excavation phases (right).*

Fault systems are characterized through the parameters shown in Table 1. These parameters are in line with the suggestions reported in the literature (Hoek et al., 1998 – Carter et al., 2008).

*Table 1. Design geomechanical parameters of fault systems: E (Elastic modulus); ν (Poisson coefficient; UCS (Uniaxial Compressive Strenght); GSI ("Geological Strenght Index"); $m_i$ (Hoek&Brown parameter).*

| | Type | E [MPa] | ν [-] | UCS [MPa] | GSI [-] | $m_i$ [-] |
|---|---|---|---|---|---|---|
| **Fault systems** | Elast. Perf. Plast. | 500 | 0.2 | 20 | 25 | 10 |

Through on-site and laboratory tests, the different lithologies were characterized with the parameters shown in the following Table 2.

*Table 2. Design geomechanical parameters for the different lithologies (Basalt_c=competent, Basalt_f=fractured): E (Elastic modulus); ν (Poisson coefficient; c (Cohesion); ϕ (Friction angle); Ψ (Dilation angle).*

| | Type | E [MPa] | ν [-] | c [MPa] | ϕ [°] | Ψ [°] |
|---|---|---|---|---|---|---|
| **Basalt_c (class III)** | Elast. Perf. Plast. | 7500 | 0.20 | 2.17 | 41.1 | 0 |
| **Basalt_f (class IV)** | Elast. Perf. Plast. | 3060 | 0.20 | 1.18 | 28.0 | 0 |
| **Basalt_f (class III)** | Elast. Perf. Plast. | 4760 | 0.20 | 1.64 | 34.7 | 0 |
| **Pyroclastic layers (class IV)** | Elast. Perf. Plast. | 710 | 0.20 | 0.71 | 19.7 | 0 |
| **Old MAT (concrete)** | Elastic | 10000 | 0.25 | 2.00 | 40.0 | 0 |

Hydrojacking tests has been carried at depths that cover the entire sector of the cavern complex (from approximately -290m to -520m), by means of which it was possible to determine the design in-situ stress. Vertical principal stress $\sigma_v$ is assumed equal to 10 MPa, while the maximum and minimum stress ratios (from which the maximum ($\sigma_H$) and minimum ($\sigma_h$) horizontal stresses can be obtained) are reported in (1). The orientation of these principal stresses with respect to the complex is shown in Figure 1 (right).

$$K_H = \sigma_H / \sigma_v = 1.5 \qquad K_h = \sigma_h / \sigma_v = 0.7 \qquad (1)$$

## 3. FEM 3D ANALYSIS AND SUPPORT SYSTEMS VERIFICATION

### *3.1 Support systems*

Support systems considered in the FEM model are, in addition to a shotcrete layer class C28/35 with wire mesh (thickness 35cm), those shown in Table 3. They are in accordance with the indications of Hudson & Feng, 2015 in the hypothesis that the complex is located in rock type IV.

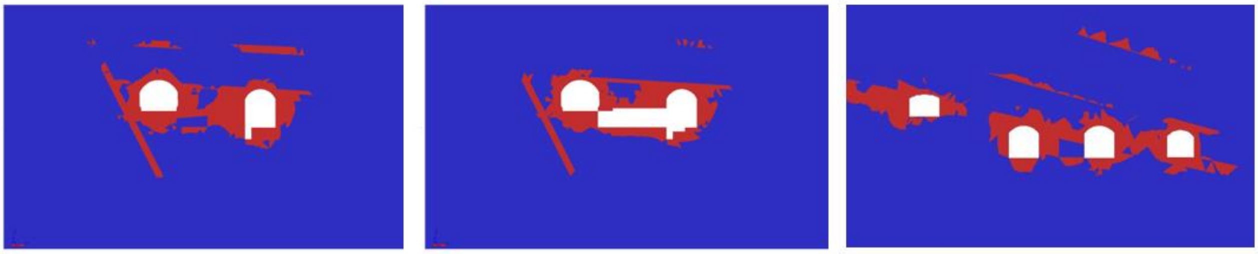
*Table 3. Support systems included in the model (Φ =Diameter; T =Tensile capacity).*

| | Type | Grid | Φ [mm] | Length [m] | T [KN] |
|---|---|---|---|---|---|
| **Rock dowels ϕ25** | Steel bars, corrugated and injected | 1.5x1.5m | 25 | 6 | 190 |
| **Rock dowels ϕ28** | | 1.5x3.0m | 28 | 8 | 246 |
| **Rock dowels ϕ32** | | 1.5x1.5m | 32 | 8 | 320 |
| **10-strand tendons** | Pre-tensioned tendons with 10 strands | - | 50 | 35 (8m bond length) | 2790 |

### *3.2 Results of the analyses*

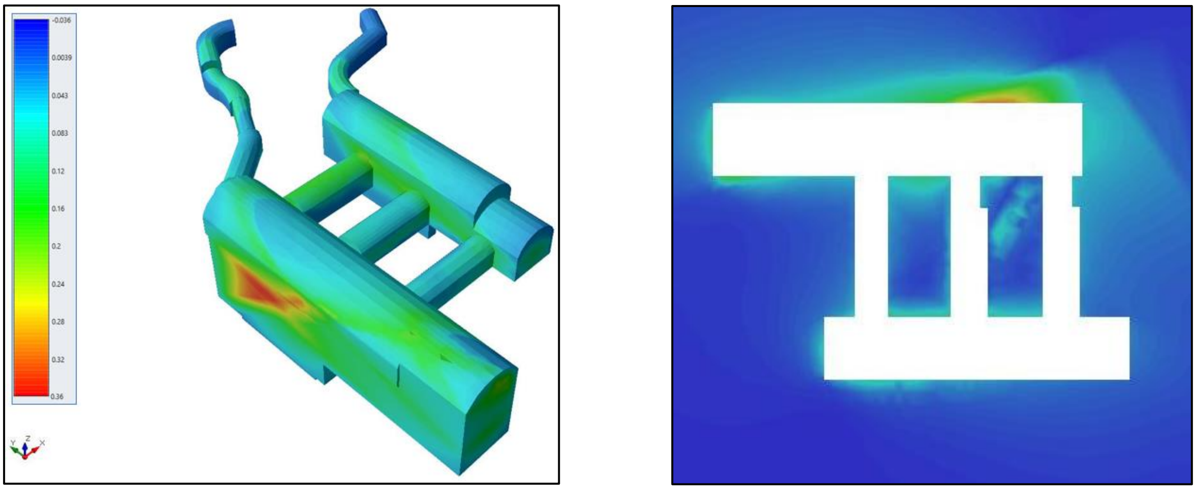
The results first show the extent of the plastic zone between the caverns and between the BSTs (Figure 4), that can reach values up to 20m (it can be noticed their development mainly along faults and pyroclastic layers in correspondence of the excavations).

*Figure 4. Plastic zones in the vicinity of the excavations.*



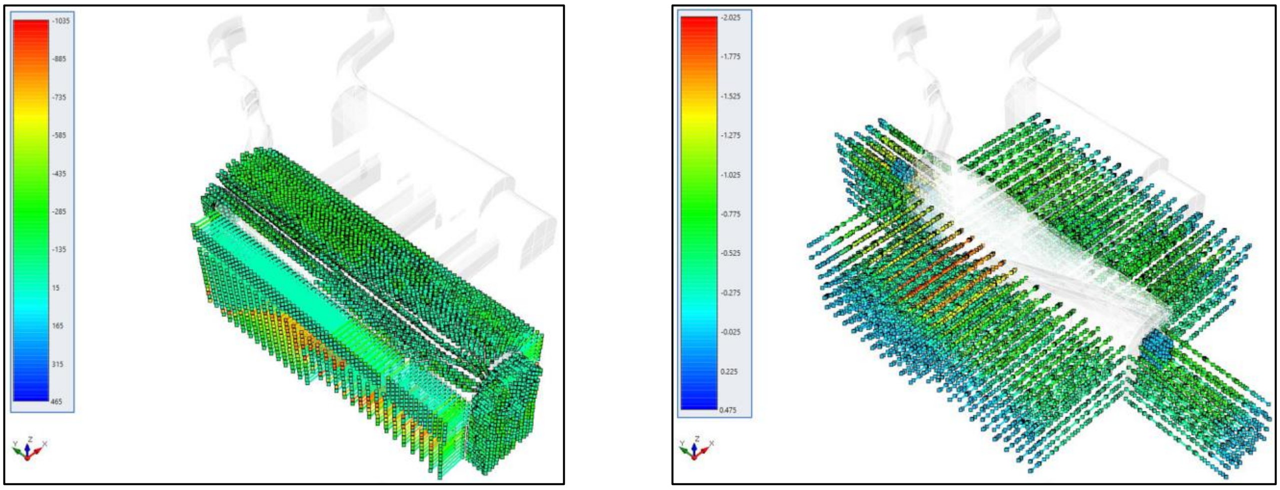
The cavern that presents the most critical issues, mainly because of the vicinity with the major fault system, is the PH. In particular, in correspondence of the upstream wall as highlighted in Figure 5, total displacements up to 35 cm have been computed. In that zone proper countermeasures shall be adopted in order to mitigate the risk of collapse, also in anticipation of the installation of generation technological units.

*Figure 5. Values of total displacements (expressed in m), perspective (left) and plan (right) views.*



The axial stresses on rock dowels (Figure 6-left) shows average values of around 400 MPa, however peak values up to 850 MPa are reached in the critical zone of the cavern (in that zone the support verifications are not satisfied). Strand tendons show the same trend, with an average value of 1100 kN of axial force computed, with peaks up to 2025 kN in critical zones of upstream wall (Figure 6-right).

*Figure 6. Axial stresses (MPa) in rock dowels (left) and axial forces (MN) in tendons (right).*



## 4. CONCLUSIONS

In conclusion, it was shown how 3D finite element analysis can represent a valid tool for the accurate determination of the critical areas of the project and the appropriate choice of support systems. Fundamental is the work during the setting up of the model, with special attention to the correct generation of the different lithologies. The results presented in this document have been used to understand the behaviour of the complex, confirm the assumptions and analyses obtained by other parties and correctly design the support systems. Ultimately, it is important to understand that the quality and costs of using advanced tools must be consistent with the level of uncertainty at all design stages.

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