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Decisive design basis and parameters for power plant caverns

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ABSTRACT: The demand on pumped storage plants for energy storage and for covering peak current has been increasing significantly during the last years. Simultaneously, standards for environmentally and ecologically friendly design of power plants have been set at higher levels. As a consequence power plant cavern with cross-sectional areas of >1500 m² are executed by an increasing number. In this paper, some dependencies concerning decisive parameters for the preliminary design of power caverns are presented. These plots may provide a first idea concerning required size of a cavern as a function of the required capacity as well as regarding support as a function of rock properties.

1 Introduction

Currently, the focus lies on the production of renewable energy. This is a politically promoted and socially supported trend.

Already today's energy mix requires facilities that store energy during the possible time lag between production and consumption. With the increasing promotion and installation of renewable energy (such as wind and solar parks) this time lag and energy volume get more variable and hence the requirements on storage volume and "production on demand" increases.

One possibility to overcome the shortage of energy storage volume and energy production on demand lies in the availability of pumped storage plants (PSP). Therefore, the number of PSP under construction is currently growing.

In order to design economically and to consider all required boundary conditions, such as the environmental impact, it is common practice to place machines and transformers in underground caverns. As a consequence of the above mentioned tendencies in terms of capacity, the requirements with respect to the size of caverns grow.

From a rock mechanics perspective, this implies that excavation and support of caverns in rock get more challenging. Among other boundary conditions this is due to the size of caverns, complexity of access tunnels, geological conditions and due to tighter schedules for design and construction.

Even though preferred geological boundary conditions in sound rock may be given, due to the interaction between rearrangement of stresses and rock strength, plastic zones in rock are developing, which may lead to deformations up to several centimetres. This tendency is supported additionally by the tight arrangement of tunnels, galleries and shafts required for operation and maintenance as well as the distance between powerhouse and transformer caverns (see Figure 1), which - from the construction cost point of view - is preferred to be as small as possible. Then again, the rock pillar between the two caverns has to fulfill design requirements in terms of strength and stiffness.

In the last decades, many large caverns for power plants have been constructed. For the design it is desired to use the experiences made during the construction of caverns as data from "full scale experiments" to validate the design of a planned cavern and hence to minimize the risk already in the (pre-) feasibility phase.

The preliminary study presented in this article provides an attempt to correlate decisive parameters for the machine cavern in order to get a first idea of geometrical requirements and of expectable deformation tendencies and to provide a tool for a first assessment of required support and deformation behaviour. The goal for this study was to provide a tool for a first estimate of the required cavern size and expected deformations and required support, starting from the planned capacity of the power plant. The provided data interpretation herein is performed by outlining qualitatively the expected range of data and is not based on statistically sophisticated correlation curves.

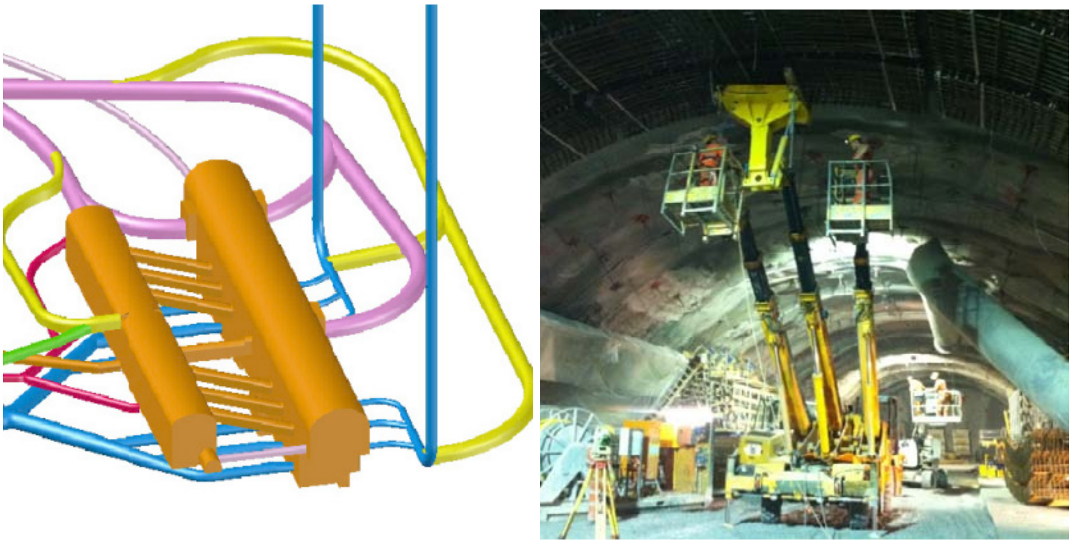

Figure 1. Example of a underground structures in the vicinity of a power plant cavern with machine and transformer caverns and tunnels for construction, access and operation (left) and installation of support in a cavern (right)

Some preliminary results of possible dependencies have been published by Saurer and Marcher (2011). Here, these data are updated using a broader basis of available data including fundamental rock parameters, deformation measurements and support reactions from current projects. In this paper, an advanced decisive design basis for the excavation of power plant caverns is presented.

2 Parameter identification

The preliminary design concepts of a power plant cavern needs to consider a variety of boundary conditions related to the requirements during operation and the boundary conditions provided by the bedrock. These include in terms of geometry the size and shape of power cavern and transformer cavern and the location of these caverns relative to each other and to the ground surface.

With respect to the rock mass the initial field stresses, and the discontinuity planes on the stability of the cavern excavations have an impact on the orientation and the choice of most appropriate support systems. These have to meet economical and safety requirements and have to be appropriate for the characteristic rock mass properties.

Furthermore, constraints imposed by mechanical, electrical and hydraulic considerations have to be considered.

In the present study, the main parameters considered are the following:

- The total (maximum) capacity P of the PSP in hydraulics can be calculated by $P = p \times Q$, where p denotes the pressure and Q is the volumetric flow, Besides the annual electricity production, which is not considered herein, the maximum capacity is the main specification factors for power plants.
- The net water head h_{net} is the factor which influences the pressure p, which is calculated by $p = h_{net} \times \gamma_w$, where γ_w is the unit weight of water.
- The cavity size is considered by a simplification using rough values of the dimensions: length (L), width (W) and height (H). Correspondingly the base area (W x L); cross-sectional area (W x H) and volume of the cavern (W x L x H) are considered.

- The overburden height h above the cavern is assumed here to affect the primary stress field of the rock mass linearly.
- Finally, the parameters of rock considered are the stiffness of intact rock E_{int} and rock mass E_{rm}; as well as the uniaxial strength of rock UCS_{int} and rock mass UCS_{rm}.

3 General Design Layout

3.1 Cavern shape

From a geomechanical perspective, the ideal shape of a cavern should be related directly to the design parameters as listed in the previous chapter. However in reality the literature review revealed that neither geometrical conditions nor rock parameters (in particular the strength) show a clear dependency with the cavern shape. This is sad because in fact the optimum shape of the cavern would be the one with a minimized moment in the concrete lining. The most common shapes found in the literature for the design of caverns are shown in Figure 2.

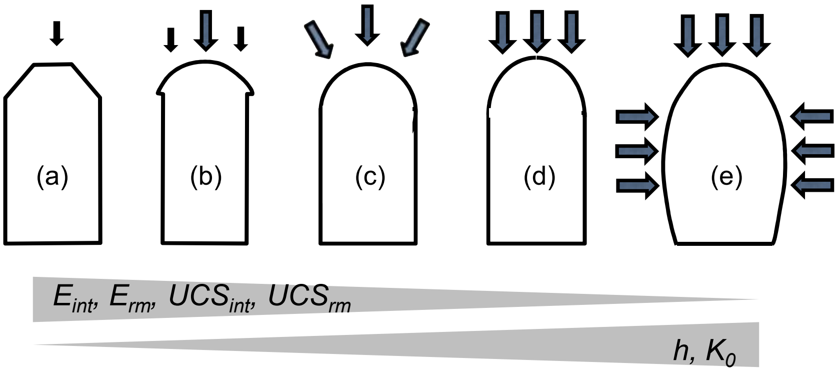

Figure 2. Common shapes of caverns; (a) trapezoidal; (b) mushroom; (c) circular shape; (d) bullet shape; (e) horse shoe

In strong rock mass the conventional shape chosen for an underground powerhouse cavern may be designed with a rather flat roof and vertical sidewalls. In principle, this is analogous to the ratio of the arch height to the length of arch bridges, which also depends on the stiffness and strength of the rock mass in the abutment. Here, in addition also the properties of the arch itself have to be considered since the arched roof provides a higher stability margin in the rock above the cavern.

With increasing overburden h, it is advantageous to have the machine cavern side walls slightly curved in order to avoid high tensile failure zones and to reduce support requirements (see Saurer and Marcher 2011).

The problem with cavern shapes as presented in Fig. 2 (a-d) when used in weak rock masses, particularly with high horizontal in situ stresses, is that tall straight sidewalls may be deflected inwards and tensile failure may be induced. In such caverns, the stabilisation of the rock mass surrounding the cavity will require significant reinforcement in the form of grouted cables or rock bolts. This may be overcome by using a horseshoe cavern shape as illustrated in Fig. 2(e). The disadvantage of such a shape is that the construction has to be executed more profile cautious than the straight-walled cavern.

Additional dependencies might be found when including anisotropic behaviour of rock mass and the proximity of the cavern to faults or weak rock zones. Due to lack of related data from cavern constructions reported in the literature no significant results can be presented but require to be investigated.

3.2 Pillar width between caverns

Transformer caverns are frequently located in a separate cavern parallel to the power cavern. In this context, the width of the rock pillar separating the two caverns is a critical design element. In addition the arrangement of tailrace, access and cable galleries intersecting the rock pillar between the caverns reduce the global strength of the pillar.

As a design rule, the zone of overstressing in the rock pillar shall be kept as small as possible both as regards tension and compression. Marcher et al. (2013) illustrate results of analyses in which the distance of the caverns has been varied. The optimization criterion for the distance between the two caverns has been set such that due to the excavation of the second cavern, the wall displacements of the already excavated cavern should not increase by more than 10%.

4 Interdependency between geometry and capacity of the cavern

Starting from the capacity of the turbines installed in the cavern,dependencies with the geometrical data of the cavity have been analysed. While the dependency between the capacity and the volume of the cavern is promising (see Figure 3, left plot), it has been found that for the cross sectional area (B x H) and the area of the cavern (L x B) dimensions are not only dependent on the installed capacity. However, as shown in Figure 3 right side, the cavern height seems to have a correlation with the capacity.

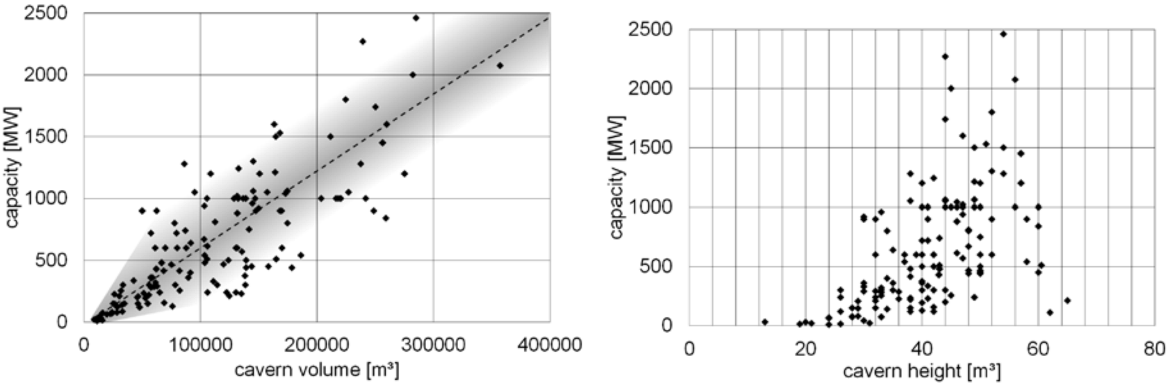

Figure 3. Dependency between capacity and cavern volume (left) and capacity and cavern height (right side)

Another attempt to find a dependency between production and cavern size has been made by dividing the capacity *P* with the net water head h_{net}. The advantage of using the net water head is that this parameter can easily be found in the literature and, for a rough estimate, it can be related linearly with the pressure p. From the equation shown above results $P/ (h_{net}) = Q \times \gamma_{w.}$, Due to the fact that γ_w is a constant, division of the capacity by the net water head is a linear function with the flow rate. It has been expected that the cavern size may depend on the amount of water that has to be processed per second assuming that the velocity ranges may be assumed to be approximately constant to maintain laminar flow. The dependency between the capacity divided by the net water head (I,e, a linear function of the flow rate) and the cavern volume and height is shown in Figure 4. In conclusion, one of the reasons for the variability of the dependencies might be found from different water flow velocities.

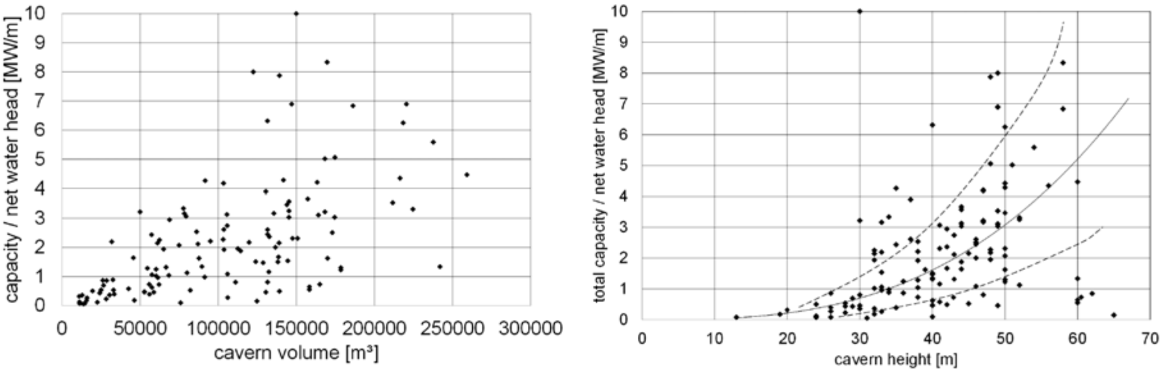

Figure 4. Dependency between the ratio capacity/net water head and cavern volume (left side) and cavern height (right side) respectively

5 Importance of geotechnical parameters

In strong igneous and metamorphic rocks the stability of large caverns at depths of less than 500-700 m below surface generally depends strongly on discontinuity driven wedges and blocks released by the degree of freedoms due to the excavation. Taking such conditions into account the excavation profile can be controlled by advanced blasting techniques. Excavation sequence depends on equipment used. Resulting displacements are relatively small.

In case of weaker (e.g. sedimentary) rocks, the strength of the rock mass will guide the design of the cavern. The surrounding rock mass may be subject to deformations exceeding 100 mm at the cavern alignment. Taking such conditions into account, support will usually be required immediately after excavation considering a clearly staged excavation procedure.

A proposal for the definition of anchor length as a function of the height of the sidewall has been proposed by Hoek 1999. The data from literature shown herein have been plotted and compared with this proposal for both passive and active prestressed anchors. The results qualitatively correlate well and are shown in Figure 5.

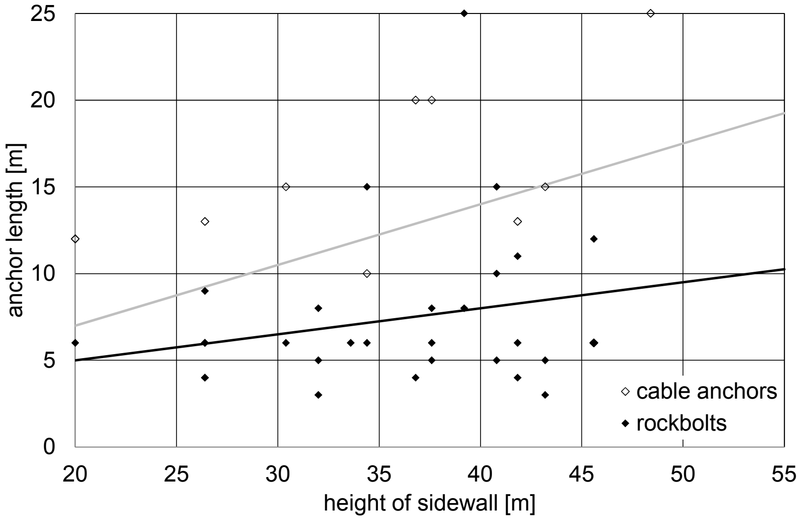

Figure 5. Anchor length (cable anchors and rock bolts) plotted against the height of sidewalls. The black and grey lines denote the dependencies after Hoek, 1999

Commonly, the maximum allowable deformation is defined at 2‰ for the vertical crown displacement and 1‰ for the horizontal sidewall displacement. From several projects and from the literature, the normalized measured displacements are shown in Figure 6. While for the sidewall, this criterion is commonly satisfied, the crown settlements exceed the limit more frequently. Still, these criteria seem to be appropriate in most cases in homogenous rock beyond the distance of influence from weak rock zones.

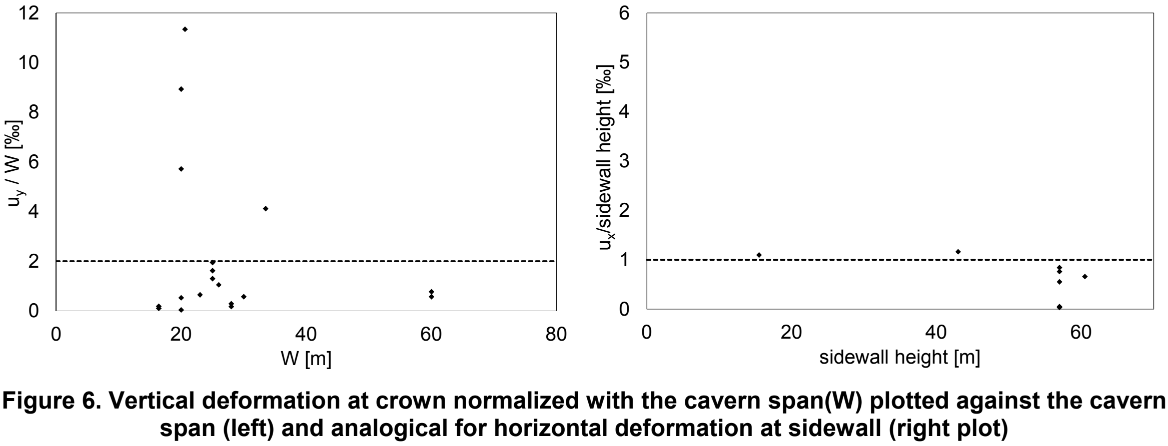

Figure 6. Vertical deformation at crown normalized with the cavern span(W) plotted against the cavern span (left) and analogical for horizontal deformation at sidewall (right plot)

Hoek 1999 published a proposal for the required support of cavern as a function of the rock quality index Q and the sidewall height. Although the Q-system is not the preferred method of the authors, it has been used to be able to compare and verify the proposal for the cavern support using the collected data. The resulting Q and sidewall height are compared with Hoek's proposal (which is based on Barton's original table for tunnels) and is plotted in Figure 7. As can be seen, and what is intrinsically expected, caverns are mainly built in rock of very good rock. This means that using the data collected herein the very right part of the diagram can be verified. On the other hand, since the database of caverns used for the plots herein is representative for caverns related to hydropower (Hönisch 2010) it remains unknown if the part of the plot on the poor side (left side) from good rock should be used for cavern design and is in general not recommended.

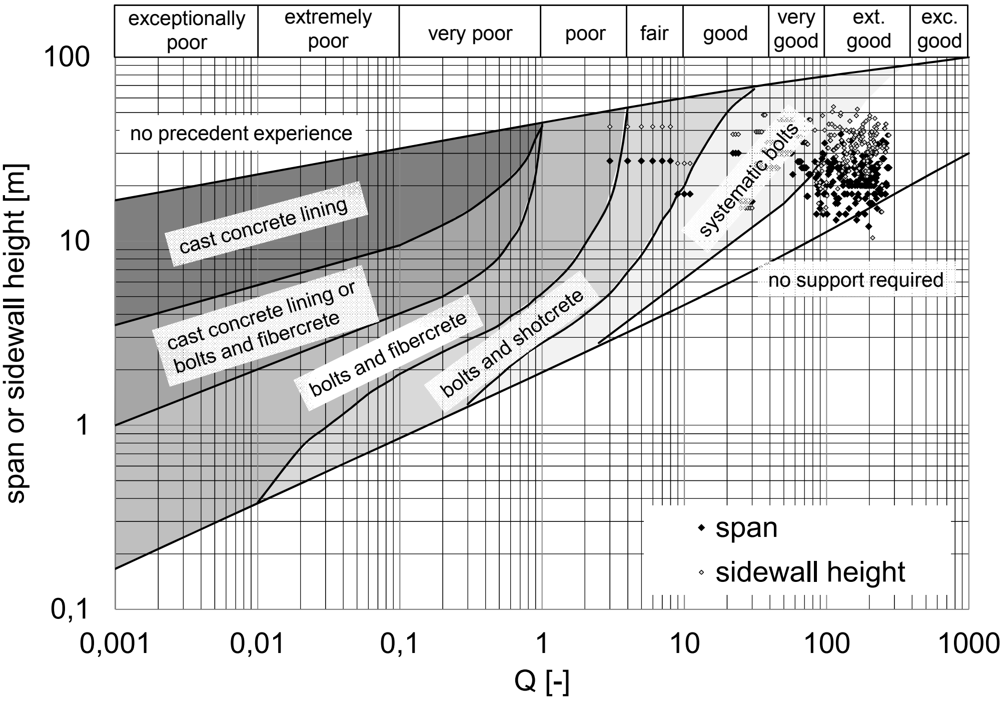

Figure 7. Comparison of data referred herein with the experiences for support proposed by Hoek 1999

6 Summary

A data set to evaluate decisive parameters for power plant caverns is presented. Different dependencies between decisive parameters have been investigated. The shown plots between capacity of the hydropower plant and the geometry of the main cavern may be used as a first assessment at an early design stage for power storage plants or may serve to cross check defined geometries.

Furthermore, dependencies between cavern geometry and geotechnical properties have been analysed with respect to expected deformations at the crown or sidewalls. A comparison between cavern supports as function of rock properties and cavern size is presented.

The data shown here represent a range of possible dependencies. Continuous collection and implementation of decisive parameters, in particular rock properties, support systems and measured deformation, into the database will further increase the significance of the dependencies.

It has been demonstrated by a comparison with the rock quality that most caverns are built in very good rock. Still by being aware of geomechanical and geometrical interactions the design of the cavern shape might be optimized in order to further reduce the risk of failures and to minimize the cost for support. The data provided hereon shall provide plots to get a first idea and order of the size and expected behaviour and does not replace required fundamental analysis.

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