In situ testing and monitoring of tunnels and caverns at a pumped-storage power plant in the Swiss Alps

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ABSTRACT: The pumped-storage power plant Limmern in the Swiss Alps was an important hydropower construction project in the last decade. To pump water from the lake Limmern to the lake Mutt, located about 600 m higher up, a new underground machinery centre and a new gravity dam for the lake Mutt was constructed. The design required comprehensive investigations of rock parameters. Preliminary investigations included hydraulic testing and dilatometer and hydraulic fracturing tests. The results were used to improve the models of the underground and to adjust the design of the three caverns. During the construction of the central machinery cavern, a complete data set of the convergence behaviour was obtained from anchor forces and extensometers. Another task was the long-term monitoring of the lake Mutt dam. Therefore, 166 sensors were installed and connected to a central data acquisition system. The combination of in situ measurements and monitoring of critical geotechnical parameters for the design and during the construction of the pumped-storage power plant was essential for the optimization of the construction process by reducing uncertainties regarding the subsurface properties and their associated risks. The final geotechnical monitoring of the lake Mutt dam continues as integral part of the safety surveillance of the dam.

1 INTRODUCTION

Since 1968, the original Linth-Limmern power station with the Limmern dam, located in the Swiss Alps in the Canton of Glarus, was fully operational. To increase the peak-shaving capacity in meeting fluctuating electricity demands, the project "Linthal 2015" for the underground pumped-storage power plant Limmern was one of the most important expansion projects of Axpo, a Swiss energy utility. Water is pumped from the storage reservoir Limmern to the upper lake Mutt, situated 630 m higher up. The pumping and turbine capacities of the new pumped-storage power plant reach 1000 megawatts (MW), increasing the output of the Linth-Limmern power plants up to 1420 MW. The project realization took one decade between the decision of the local government and the start of full operation in 2017. Pressure, head race and access tunnels as well as three large caverns (max. length 150 m, max. width 29 m and max. height 51 m) for the turbines, power house and valve chamber were excavated and a large gravity dam built to increase the storage volume of the lake Mutt. A comprehensive hydrogeological and geotechnical in situ testing and monitoring program was implemented (Becker et al. 2017). An overview is given in Figure 1.

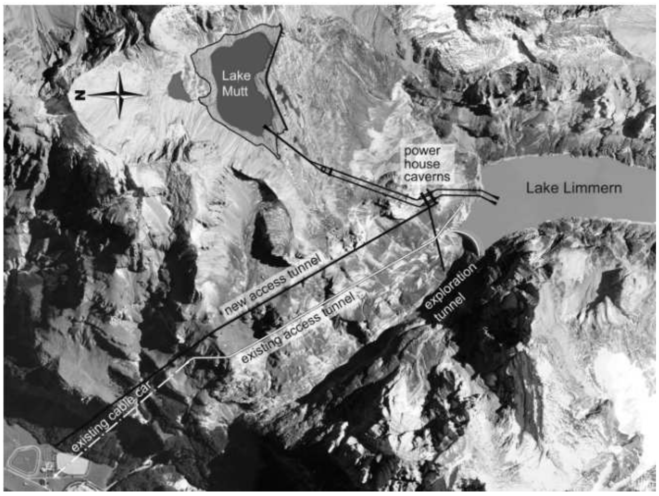

Figure 1. Overview of pumped-storage power plant Limmern

2 PRELIMINARY IN SITU TESTS

The central cavern is partly located in the Quintner limestone of Malm and Cretaceous origin with locally developed schistosity and karst formation. Because of the extension of the caverns, the hydraulic and rock mechanic properties were estimated during a preliminary investigation phase. Therefore, in situ tests were performed in ten boreholes between horizontal and upwards vertical direction with a diameter of 96 mm

(HQ) and a length of maximum 130 m. The locations of the boreholes are shown in Figure 2. The main goal of these in situ tests was:

- Information on rock structure, schistosity, fractures, faults, karst
- Determination of the mechanical rock properties, elasticity and deformation moduli by dilatometer tests
- Determination of the minimal principal stresses by hydraulic fracturing tests
- Identification of water-bearing features and determination of static formation pressures and rock permeabilities by hydraulic tests.

The task was particularly demanding, as all the tests had to be performed in boreholes drilled from small exploration tunnels without the help of the drilling crew (Fig. 3). The particular boundary conditions of the test sites and the relatively short time window for the performance of these extended test series in combination with the logistic challenges required a careful planning and a novel testing approach for the more time-consuming implementation of the hydraulic tests.

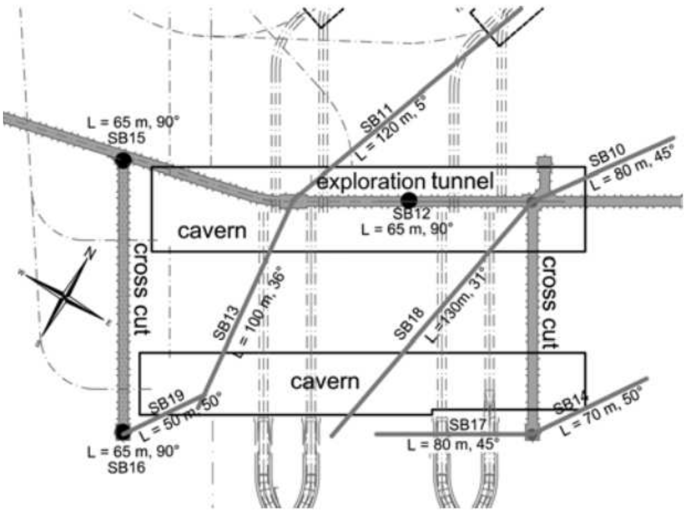

Figure 2. Location of boreholes and future caverns

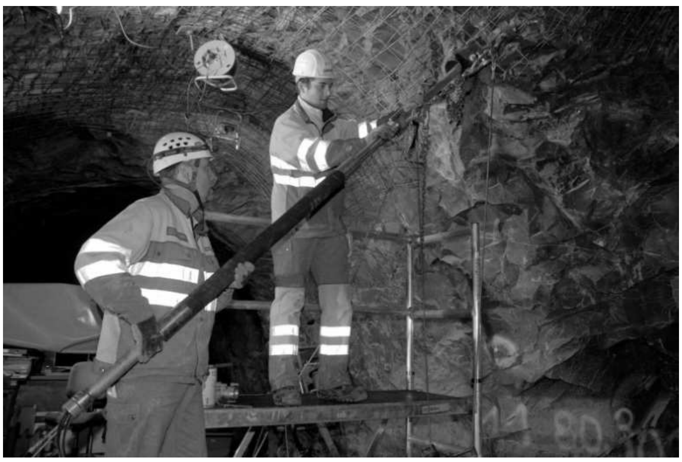

Figure 3. Installation of the multi-packer system

The main challenge was the performance of the hydraulic tests. To avoid the slow natural saturation of the de-saturated formation due to the drilling of the upwards inclined boreholes and the trapping of air in the intervals, a customized 4-fold packer system was developed (Fig. 4). In total, three similar systems were simultaneously used to cope with the time limitations. The advantages of the systems can be summarized as follows:

- Saturation of the entire borehole after inflation of the packer nearest to the well head
- Simultaneous de-airing of the boreholes through the line situated at the bottom of the system
- Simultaneous monitoring and performance of parallel hydraulic tests in different intervals because of two individual lines within each test / observation interval (Fig. 4)
- Long-term monitoring of the pressure recovery
- Optional cross-hole tests.

A total of 40 hydraulic tests were performed. In addition 55 dilatometer tests, 23 hydraulic fracturing tests and 18 impression packer tests were conducted without problems. Dilatometer tests supplied reliable ranges of in situ rock E- and D-moduli. Hydraulic fracturing tests defined principal stress magnitude and orientation (Kech et al. 2010). The results were important for the proper design of the caverns and the optimization of the layout and the construction work (Marclay et al. 2010, Müller et al. 2013).

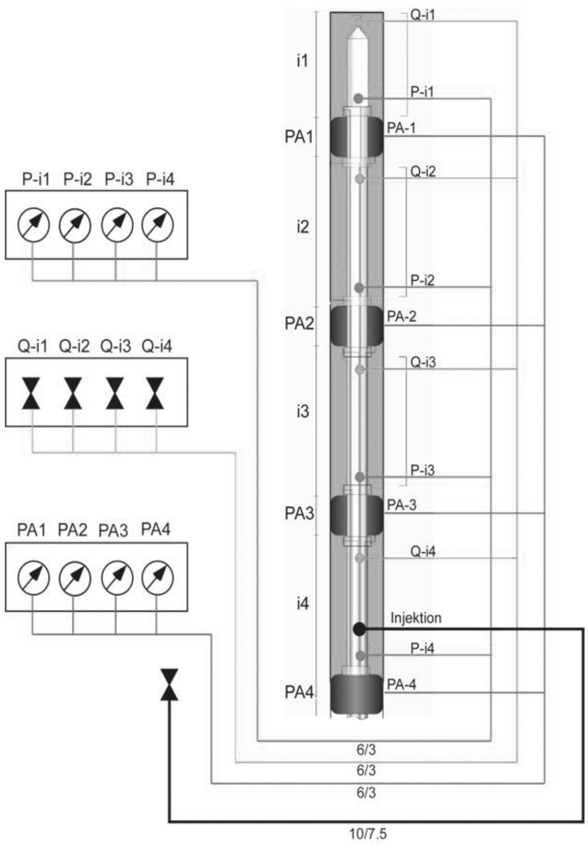

Figure 4. 4-fold packer system used for hydraulic testing

Figure 5. Drilling site of an exploration borehole at the lake Mutt

In addition, the hydraulic properties of the debris cones around the lake Mutt were investigated (Fig. 5). Hydraulic tests were performed in three boreholes up to a depth of 38 m using a standard double-packer system. These tests provided essential information, which was used to estimate the debris behaviour under the expected lake level increase from 2446 m asl to 2474 m asl and the water level changes during the operation of the power plant and to prevent slope instabilities along the lake Mutt.

3 MONITORING OF CAVERN EXCAVATION

The excavation of the central machinery caverns, consisting of machine and transformer caverns and the valve chamber (machine cavern; see Fig. 6) was performed from top to bottom.

Figure 6. Machine cavern during 2012

This required a continuous monitoring of the rock deformations and the anchoring forces during the excavation process. The convergences were recorded with 30 m long 4-point extensometers, installed in cross-sections (Fig. 7). As the extensometers were immediately installed close to the working surface to obtain a complete data set of the convergences, their heads had to be protected from the potential damage by blasting. Initially the extensometers were equipped with data loggers and were wirelessly readout. In a later stage, the extensometers and the anchor load cells were connected via a bus cable (Fig. 8) to a central data acquisition system and subsequently uploaded to a Web database with close-to-real-time data plots, which were available to the responsible engineers at their workstation for permanent control.

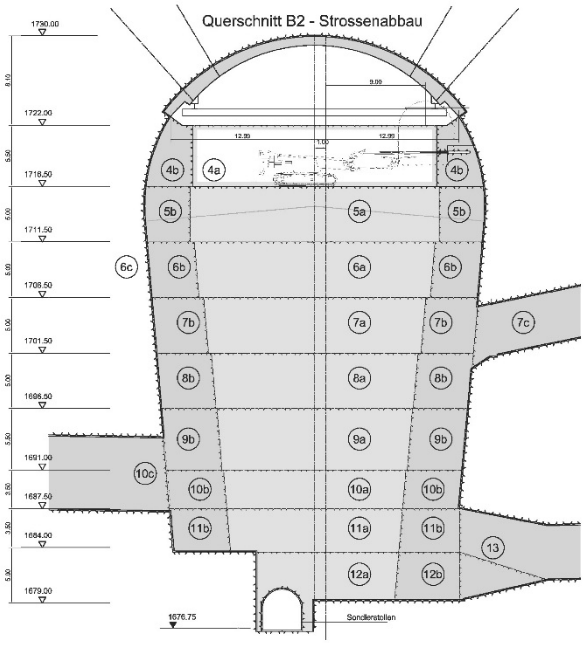

Figure 7. Cross-section of machine cavern with excavation stages and uppermost extensometers

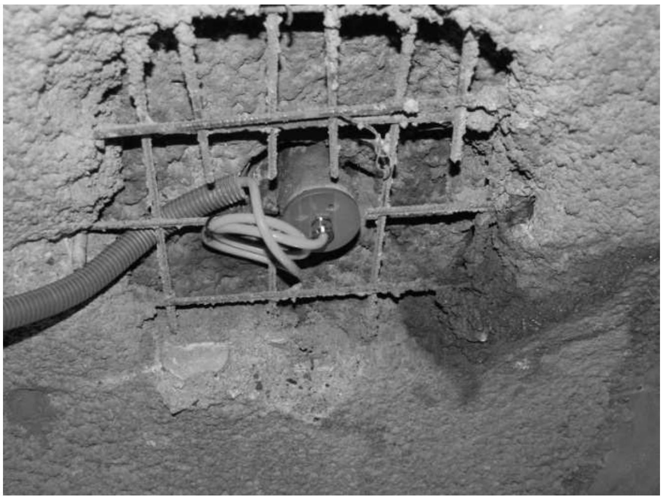

Figure 8. Extensometer head with bus cable

4 INSTRUMENTATION OF LAKE MUTT DAM

The new dam of the lake Mutt has a length of 1050 m and a height of 35 m and is Europe's longest gravity dam. The total volume of the lake is thus increased from 9 to 25 million cubic meters. The installation of the dam safety monitoring started in 2015 and included:

- 76 pressure sensors for flotation measurements
- 74 concrete temperatures
- 7 seepage surveillance points
- 8 pendulums
- 1 lake water table measurement station.

Solexperts obtained the task to install the flotation measurement points. Eleven cross-sections were instrumented. The flotation, which normally depends on the lake water level, is measured at different depths in the underground and at the contact between concrete and rock. The boreholes were drilled from the control gallery over the entire foundation width to monitor the pressure potential decrease from the upstream to the downstream side of the dam (Fig. 9).

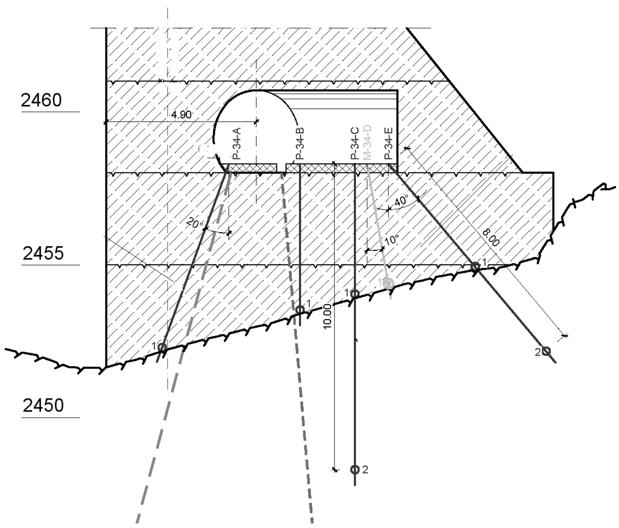

Figure 9. Measuring sections in the lake Mutt dam, dark solid lines represent the flotation measurement boreholes

One to three vibrating wire pressure sensors were installed at different levels in each borehole. One measuring position in each cross-section was equipped with a retrievable pressure sensor using a Solexperts Piezopress system consisting of a plastic casing with a filter element and the sensor seat at the bottom (Fig. 10). After the installation of the casing, the borehole was filled with sand along the filter section and with a cement injection as sealing section. The sensor was installed after the backfilling at the sensor seat in the filter section and sealed to the casing by O-rings. The other sensors were directly installed as lost sensors at the required depth in a sandy filter section, which was isolated by cement injection to avoid a hydraulic short circuit between different aquifers.

Figure 10. Piezopress: Installation with retrievable pressure sensor (left) and schematic cross-section (right)

Figure 11. Measuring box for the flotation measurements with digital displays of the current heads

All sensors installed in one measuring section are connected with a measuring box with the possibility to manually readout the sensors. Furthermore, the sensors are connected to the automatic data acquisition system and the current calculated heads are automatically displayed at the front of the measuring box (Fig. 11).

Besides the flotation, further parameters are monitored. The concrete temperature sensors are installed in several cross-sections and primarily serve for the quality control of the concrete. The seepage water is collected in a canal along the downstream side of the dam and the water amount is measured at seven V-weirs with ultrasonic sensors. Furthermore, the position of the dam is recorded to estimate its stability. Therefore, four measuring sections are equipped with a pendulum and an inverted pendulum. The pendulum measures the inclination from the dam crest to the measuring location in the control gallery. The inverted pendulum is anchored in the rock and provides information on the relative movement of the dam with regard to the foundation. In addition, the water level in the lake Mutt is recorded.

5 DATA ACQUISITION SYSTEM

An automatic data acquisition system was installed in the dam guard cabin directly besides the lake Mutt dam. The power supply includes a UPS (uninterruptable power supply). All described instruments are readout via a data bus system. The communication of the DAS with the sensors is ensured by a backbone system and multiple sub-bus systems. Therefore, most parts of the measuring points would still be monitored also in the case when main components of the system might be subject to failure. A total of about 250 sensor channels is recorded which, in addition, are partly calculated into target units. All data is integrated in the higher-level analysis system of the dam operator.

6 CONCLUSIONS

The construction of the pumped-storage power plant Limmern in the Swiss Alps represented a major challenge. To improve the design, comprehensive investigations of rock parameters were initially required. Hydraulic tests were performed with three multi-packer systems simultaneously to obtain information on the hydraulic conductivities and the static formation pressures in the partly schistose and karstic limestone. The E- and D-moduli of the rock were determined with dilatometer tests. Finally, hydraulic fracturing tests were conducted to estimate the minimum primary stresses in the rock. Another task was the convergence monitoring during the construction of the central machinery cavern with anchor forces and extensometers. The long-term monitoring of the new dam of the lake Mutt was implemented by the installation of 166 sensors, including pressure sensors for flotation measurements and lake level monitoring, sensors for temperature and seepage measurements and pendulums.

The entire testing and monitoring program proved to meet to the requirements and the results were essential for the optimization of the design and the construction process. Furthermore, the long-term monitoring of the newly built lake Mutt dam provides substantial information on the dam performance which is necessary for the safe operation of the pumped-storage power plant.

7 REFERENCES

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