The Linth-Limmern hydro-power plant – Design and construction of a large pumped storage scheme

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ABSTRACT: "Linthal 2015" stands for a couple of records – Switzerland's largest hydro-power plant with Europe's longest concrete dam, a huge construction site at an altitude unique in Europe, and a stunning logistics with two of the largest cableways ever built. The paper describes the design philosophy, the development of the main project – covering the hydraulic system and the underground works – and the steps taken to optimize the layout, the dimensioning and the sequencing of works. Challenges are the ambitious time schedule, the logistics, the concerns for the delicate alpine nature, and last but not least the required high reliability and availability of the power plant. While this paper presents the broad picture of the project, another WTC'13 paper discusses the analysis and construction of the main caverns in more detail.

1 The vision "Linthal 2015"

In 2003 the former Nordostschweizer Kraftwerke NOK, which later became part of the hydraulic division of Axpo Power AG, began to look for suitable sites to increase their peak shaving capacity in meeting fluctuating electricity demands. Nobody could then foretell the acceleration in wind and solar power generation, which makes the needs for energy storage and grid stabilization even the more pressing, Several pumped-storage upgrading projects are underway in Switzerland (RAOnline 2012), Linthal 2015 being the largest of them.

1.1 Existing facilities

Deep in the Glarner Alpes, at the end of the Linth valley about 90 km south-east of Zurich (Switzerland), a 146 m high arch dam was built in 1963, creating a 92 mio. m^3 reservoir. The hydraulic head between 2,446 m reservoir level and the valley (811 m a.s.l.) at Tierfehd generates 260 MW.

Figure 1. View of Lake Limmern (1,854 m a.s.l.)

In 2009, this lower stage was upgraded with a 120/140 MW turbine/pumping station (project "Nestil"). However, the big leap in energy generation will come by exploiting the hydraulic head of 630 m between Lake Limmern and Lake Mutt – where today just a small hydro-power station of 4.4 MW exists – as the new upper stage of 1,000 MW. The costs are estimated to 2,100 mio. CHF.

1.2 The project "Linthal 2015"

The project encompasses the following main items (Axpo Power 2012):

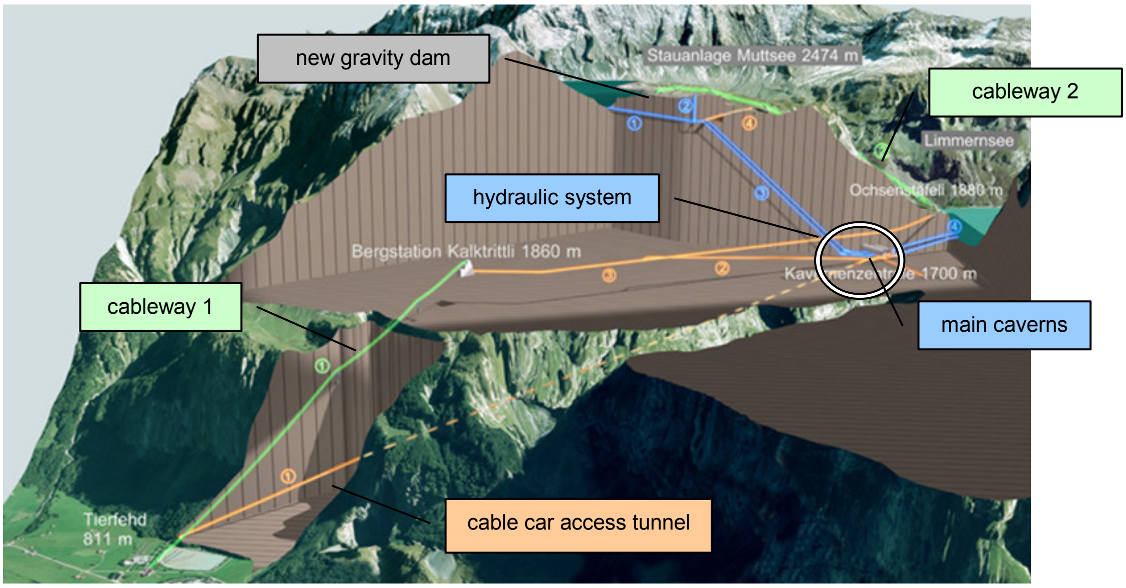

Figure 2. Cut-away graphics of Linthal 2015

- Increasing the storage capacity of Lake Mutt from 9 to 24 mio. m^3 by building a 1,000 m long gravity dam with 68 blocks of 4 - 33 m height, thereby raising the water level to 2,474 m a.s.l.
- Building an underground hydraulic system in an area of about 2 km length and 700 altitude difference with a 540 m long pressure tunnel ①, a 125 m high surge chamber ②, two 1,054 m long pressure shafts at 90% inclination, the machine and transformer caverns ③ for 4×250 MW turbine-pumps with 46/36 m^3/s discharge each, and two 405 m long tailwater tunnels ④.
- Accessing the construction sites by two 25 t cableways, one from Tierfehd to Kalktrittli (1,860 m a.s.l.) ①, the other from Ochsenstaefeli (1,880 m a.s.l.) to Lake Mutt ②, interconnected by the gallery ZS 0, with a sloping branch to the cavern level (1,700 m a.s.l.).
- Creating a permanent access from Tierfehd to the caverns by boring a 3,800 m long tunnel at 24% inclination (gallery ZS I) for a 215 t cable car, to be ready in spring 2013 for transporting the cavern equipment (turbines, generators, transformers) ①.
- Building appurtenances in the Linth valley such as additional compensation basins and a 380 kV power line to connect with the Swiss high-voltage grid.

1.3 Milestones

By virtue of a transparent process involving the canton of Glarus, environmental stakeholders such as WWF, the tourist board etc., all issues could be settled in an amicable manner and the concession was obtained within only two years (2006-2008). The engineering consortium "Alpenstrom" was engaged in 2007 and produced the basic project (except for the gravity dam and the cable car access tunnel) in 2008, such that the client Axpo could decide on the investment in September 2009. Advance works for the logistics started the same autumn, and the main construction began in spring 2010 with three lots in parallel – the hydraulic system (BA-1), the gravity dam (BA-2), and the cable car access tunnel (BA-3).

Despite severe winters with up to 4 m snow, the dam construction is advancing well, breakthrough of the first pressure shaft was in October 2011 and of the access tunnel for the cable car in March 2012. Concreting of the caverns is underway, in time for the commissioning to begin in autumn 2015.

2 Geology

Exploration started in 2005 with seismic campaigns, drillings from the surface and existing galleries, as well as driving new exploration galleries, which were later used for access and drainage.

2.1 Stratigraphic situation

The project is situated in the middle floor of parautochtonous sediments, i.e. the Quintner limestone of malm and cretaceous origin, which was broken and shifted in packages during faulting of the crystalline Aar massive in tertiary times.

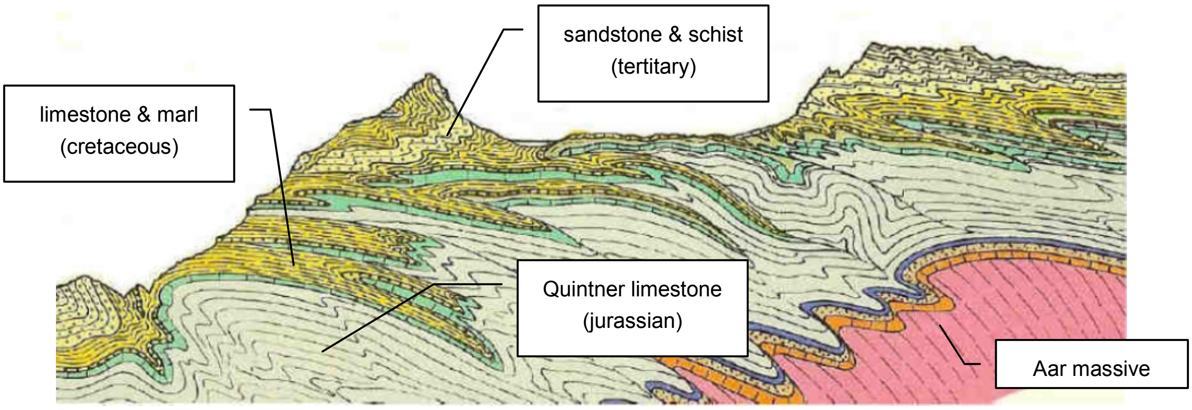

Figure 3. Geological profile SE-NW (about 1.5 km north of the cable car access tunnel)

During faulting the sediments were subjected to metamorphous compression, resulting in a schistosity dipping 40-60° SSE. The limestone is prone to karst formation, thereby enlarging existing fault systems and draining the mountain effectively. The phreatic level was predicted far below the rock surface, bounded by the Linth river at 800 m a.s.l. and the lateral narrow valleys.

2.2 Discontinuity sets

Orthogonal to the axe of faulting runs a steep joint set (K1) in SSE-NNW direction with 5-15 m spacing and a persistence varying from 2-5 m to >50 m. The joints become denser (3 m to 0.3 m) near two rupture lines, which are oriented close to K1 and 10-20 m wide. One of these, the Moertal fault, crosses right through the project area such that it must be traversed by the pressure shafts.

A second joint set K2 runs ENE-WSW parallel to the axe of faulting, and two minor joint sets K3 and K4 show up only locally. The main caverns could be orientated perpendicular to K1 but are crossed by K2. The inclination of K2 can vary about the vertical axis.

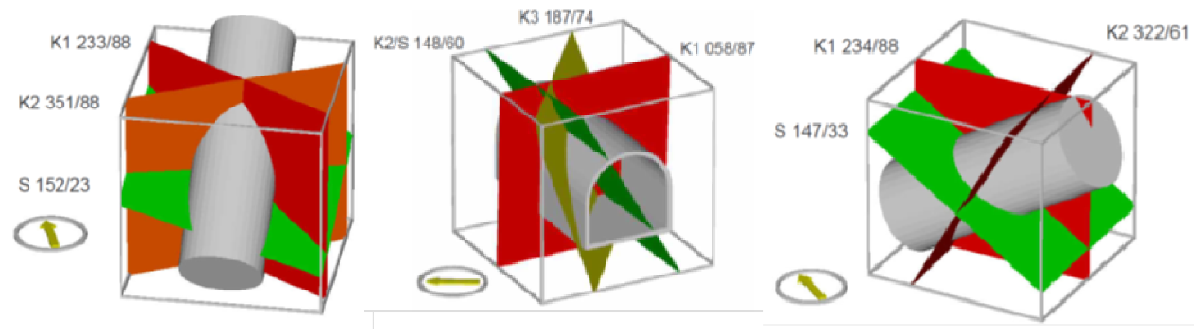

Figure 4. Block diagram of joint system (f.l.t.r: pressure shaft, main caverns, cable car tunnel)

In 2007 a horizontal exploration gallery was driven along the future base of the machine cavern, which later served for mucking and as drainage gallery. In several side galleries the orientation and persistence of discontinuities were registered along three scan lines of 10-15 m length each. Locally, some K1 joints were found to have developed into open karsts of up to 1-5 m width, without contemporary water circulation.

2.3 Rock mass properties

Stiffness and strength properties were derived from in-situ and laboratory tests, and given as likely characteristic values of the rock mass. The lower values of the band of uncertainty were expected to amount to residual properties.

Table 1. Rock mass properties (April 2008)

	E [GPa]	V [GPa]	σ_{ci} [MPa]	c [MPa]	φ [°]	$GSI_{average}$ [-]
sandstone†	16 ± 8	11 ± 5	100 ± 30	8 ± 5	36 ± 4	
marl†			40 ± 15			
limestone‡	26 ± 4	12 ± 4	66 ± 9	8 ± 5	35 ± 5	
Qintner limestone	26 ± 4	20 ± 5	90 ± 20	8 ± 4	39 ± 3	75 ± 5

† Bürgen-/Hohgant formation ‡ cretacious formations (Oerli, Betlis, Drusberg)

In later reinterpretation the elastic modulus E was raised at the expense of a lower uniaxial compressive strength of intact rock (σ_{ci}). In 2009 the geological model around the main caverns was refined, distinguishing a weaker platy-schistous zone from the surrounding massive-blocky limestone. In either zone the predicted cohesion was considerably reduced (Marcher et al. 2013).

For plausibility, the rock mass was also described in terms of the geological strength index (*GSI*). Already early in the basic project for the main caverns, a pessimistic property set had been derived by assuming GSI = 65 from a Hoek-Brown material model (Marclay et al. 2010). Thus the dimensioning from characteristic values with superimposed safety factors gave similar results as an analysis with pessimistic values.

2.4 Stress state

Some considerations were given to tectonic stresses and stress anisotropy due to the steep mountain flanks (cf. Fig. 1). It was concluded that the vertical primary stress S_V is almost lithostatic (6-10 MPa), and from hydrofrac tests in three boreholes the major horizontal stress was estimated to $S_H \approx 8$ MPa and the minor to $S_h \approx 4$ MPa.

3 Layout of underground structures

During checking of the preliminary design (elaborated by Lahmeyer International Ltd.), some optimizations in layout, detailing, construction and logistics were suggested.

3.1 Pressure tunnel and shafts

The preliminary design featured a single pressure tunnel of ∅ 8 m, which bifurcates under the surge chamber into the two pressure shafts. A fully redundant hydraulic system could have been achieved by a double pressure tunnel of ∅ 6 m, but with higher hydraulic losses during part load. The circumferential tension in the concrete lining is controlled by prestressing through injection tubes in the annual ring ('passive prestress'). The same method was applied for the tailwater tunnels with ∅ 5.5 m.

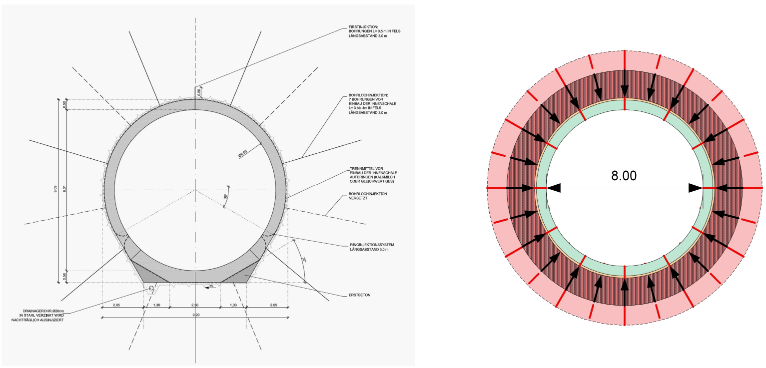

Figure 5. Pressure shaft design with passive prestress

The surge chamber was moved for topographical reason and situated behind the bifurcation between the two pressure shafts. This reduced the construction risk in comparison with the preliminary design, in which the surge chamber was suggested right above the bifurcation. The 130 m high chamber is excavated by raise-drill from the Lake Mutt plateau and lined with 60 cm reinforced concrete. A combination of two staggered horizontal chambers was considered as alternative but rejected because of the impact of the large construction pit on the landscape.

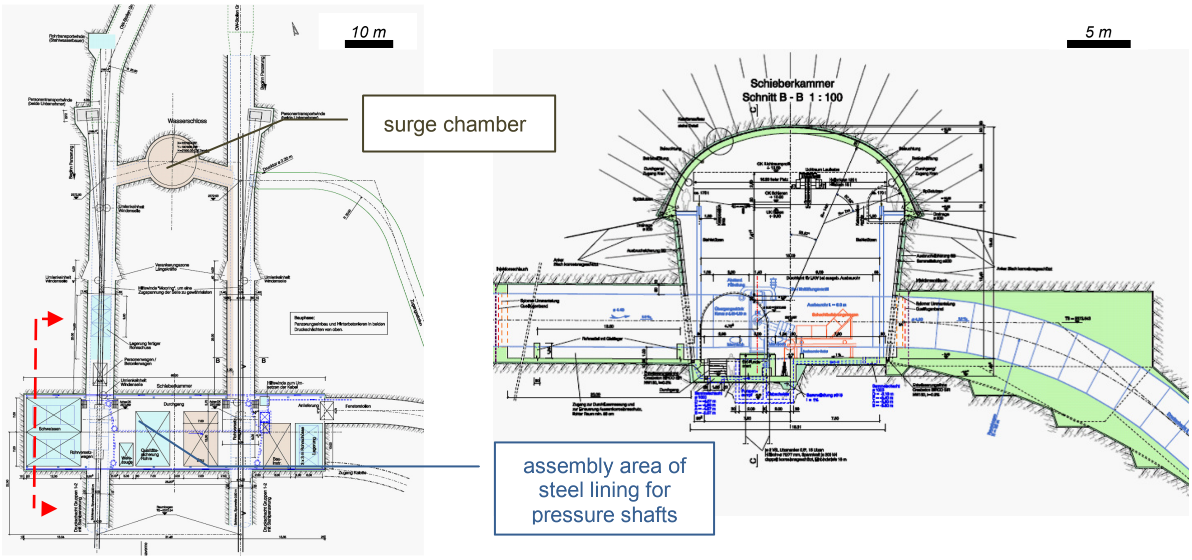

Figure 6. Layout and cross-section of the valve chamber

The alignment of the two pressure shafts was made to converge from 50 m at the foot to 30 m at the top, which allowed for a shorter valve chamber design. The pressure shafts of ∅ 4.2 m are armoured by a steel lining, welded in the surge chamber from 3 m long sections and lowered into the shafts.

3.2 Cavern layout

At the foot of the pressure shafts, a complicated network of galleries accommodates future pressure and service tunnels as well as the various temporary accesses (Fig. 7). To orientate the main caverns perpendicular to the joint set K1 and to avoid a karstic zone detected in the rear exploration gallery, the caverns had to be rotated by about 15° to the north and shifted 80 m to SE.

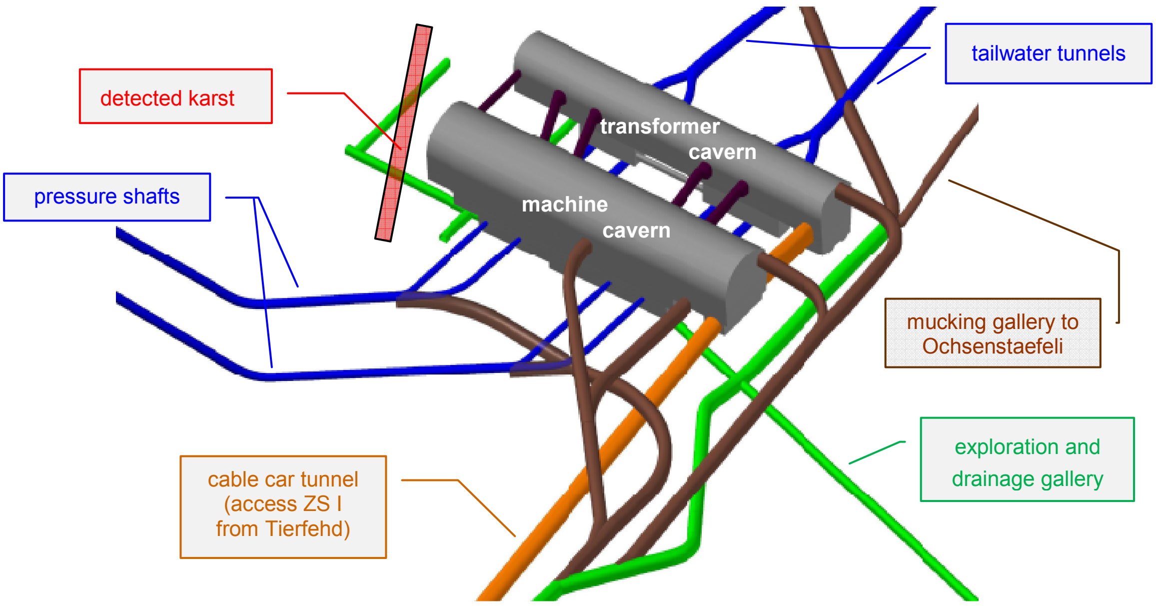

Figure 7. Visualization of optimized excavations around main caverns (view from NW)

The ‘kink’ in the pressure shafts was introduced to permit assembly of the 130 m long TBM for boring the pressure shafts of ∅ 5.2 m independent of the progress made in excavating the caverns.

In the preliminary project the distance between the machine and the transformer cavern had been assessed from an elastic 2D analysis with stress check for the Mohr-Coulomb criterion. In the basic project this analysis was refined in two directions (Marclay et al. 2010):

- 2D analysis of a single joint K2 intersecting the rock pillar between the two caverns with unfavourable dip angle for decreasing cohesion $c = 3 \rightarrow 1$ MPa
- 2D nonlinear analysis of the plastic zones with a 3D Mohr-Coulomb criterion for various combinations of the horizontal pressure coefficients K_0 = 0.28 - 0.7 in lateral and out-of-plane direction.

During tendering the distance between cavern axes was about 62 m. With the reduction in predicted rock mass strength (viz. 2.3), it was eventually decided to place the transformer cavern 25 m farther apart, in order to reduce the vertical stress in the rock pillar and to limit the influence of the transformer cavern on the wall deformation of the machine cavern to 10% (Marcher et al. 2013).

3.3 Cavern shapes

The dimensions of the machine cavern are 150 m × 31 m × 54 m, and those of the transformer cavern 130 m × 20 m × 25 m, resulting in 244,000 m^3 of excavation. The initially vertical walls were replaced by a horse-shoe shape for statical reasons (improved stress flow). The crown support is designed as slotted concrete shell of 90-150 cm thickness, allowing for drainage of the rock mass.

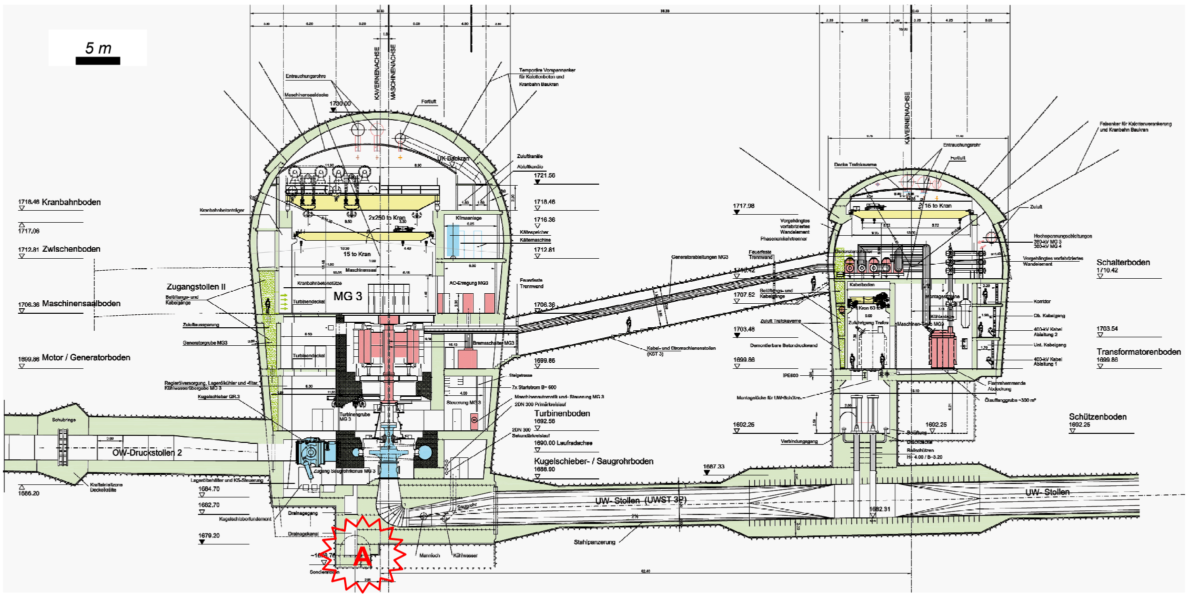

Figure 8. Cross-section of main caverns (narrow spacing before alteration)

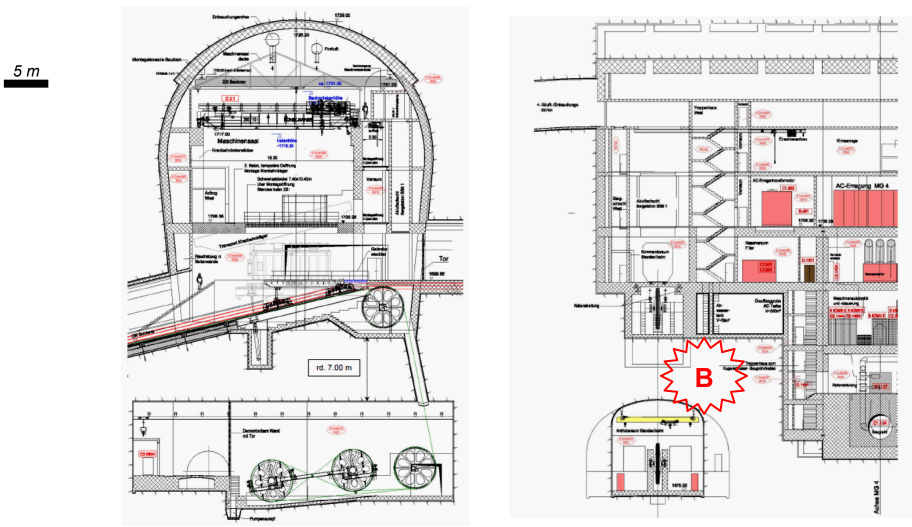

Figure 9. Face wall of the machine cavern with cable car station

The 215 t cable car arrives through the tunnel ZS I on the generator floor of the machine cavern. In the basic design, the cable was planned to run further to the transformer cavern, where the driving wheel would be housed. However, from critical path analysis it became desirable to place the power house for the cable car under the south-west face wall of the machine cavern, such that the cable car could be used as early as possible. The stress field in the small rock bridge below the machine cavern floor ('B' in Fig. 9) required particularly attention and was investigated in a 3D finite element model.

4 Functional requirements of underground structures

The utilization and safety requirements were compiled according to Swiss code SIA 260, distinguishing between ultimate and serviceability limit state.

4.1 Hazard scenarios

A top-down risk analysis – including opportunities as mentioned above – was conducted at a very early stage of the project. For instance, the hazard of a breach of the hydraulic system with ensuing flooding of the machine cavern was taken into account by arranging the exploration gallery to function as emergency discharge channel ('A' in Fig. 8). Against fire, e.g. due to an overheated generator, the mucking gallery to Ochsenstaefeli was designed as future smoke extraction shaft (cf. Fig. 7).

In geotechnical analysis the scenario distinguished between continuum and discontinuum issues. While the overall stability and deformation was checked with FEM including the modeling of rock bolts, the length and capacity of rock bolts were determined from the analysis of key blocks defined by the joint sets in Fig. 4. Even for characteristic strength parameters the predicted plastic zones exceed the length of rock bolts, which (in continuum analysis) function merely as 'floating reinforcement' (Marcher et al. 2013).

As part of the monitoring concept during excavation, warning and alarm values had to be specified in terms of observable readings, i.e. taking into account the time of installation of reflectors and extensometers according to the actual excavation sequence. The alarm values were derived from conservative FEM analysis with characteristic deformation modulus and brittle softening in overstressed ('plastic') zones; these were additionally checked against the results assuming pessimistic stiffness and strength properties throughout the domain. The warning values were simply taken 60-70% of the alarm values.

4.2 Durability

Paramount is the question of the exterior water level, not only as occurring naturally in the fissured rock, but also the hazard of a leaking tailwater tunnel leading to the build-up of a 'man-made' water pressure on the cavern walls. It was decided to drain the rock into the caverns and to assure the dryness of equipment rooms by a 'house-in-house' design with additional interior walls (Fig. 8).

No permanent anchors are foreseen in the design, but the concrete lining (together with arching effects in the rock) has to accommodate the stresses resulting from their postulated corrosion. Consequently, the anchors received just a nominal prestress to reduce slack and remained unprotected. Only the crown shell was temporarily secured with prestressed anchors, in order to carry the loads of an erection crane suspended from the abutment beams (Fig. 10), whereas the permanent crane rails will rest on the interior walls.

5 Material management and logistics

One success factor of the project is the balanced material management, where large quantities of excavated material can be reused as concrete not only for interior works (130,000 m^3), but even more for the gravity dam at Lake Mutt (250,000 m^3). Only in the first year of construction, the concrete aggregate needed to be supplied from the valley.

Building material to be transported by the cableway included about 100,000 tons of cement and 40,000 tons of steel. The design load capacity of the cableway is 25 t, which can be augmented to 40 t in exceptional operating mode. Heavier equipment had to be dismantled for transportation, such as two crawler cranes of 180 t weight and the TBM for boring the pressure shafts (700 t).

6 State of works

Few of the works suffered delay. Driving the first shaft through the Moertal fault took 6 month longer than expected, but the breakthrough could be celebrated on 14th October 2011. Also the access tunnel ZS I from Tierfehd to the machine cavern was 4 months late, with breakthrough on 20th March 2012.

Lining of the first pressure shaft has begun, while the TBM is boring the second one. The gravity dam will be completed in 2014. The carcass works of the machine cavern are planned to be finished in March 2015, such that filling of the hydraulic system can commence in April and the first machine group undergo testing in September the same year. The three other machine groups will follow suite in intervals of 4-5 months.

Figure 10. Concreting underway in the machine cavern and at the gravity dam

7 Acknowledgements

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8 References

Axpo Power AG http://www.axpo.com/axpo/ch/de/axpo-erleben/linthal-2015.html (2012, animation in German).

Marcher, T., John, M., Hohberg, J.-M., Fellner, D., Dunn, J., Marclay, R. 2013. Design and verification challenges of the Limmern caverns. WTC 2013, Geneva (submitted for publication) .

Marclay, R., Hohberg, J.-M., John M., Marcher, T., Fellner, D. 2010. The new Linth-Limmern hydro-power plant – Design of caverns under 500 m overburden. Eurock 2010, Lausanne. Rock Mechanics in Civil and Environmental Engineering, pp 467-470, Taylor & Francis.

Marti AG http://www.argekwl.ch/go/Bautagebuch (2012, construction diary in German).

RAOnline http://www.raonline.ch/pages/edu/nw/power01a4a101.html#start (2012, in German).