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Design and verification challenges of the Limmern caverns

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ABSTRACT: A 1,000 MW pumped-storage plant is under construction at altitudes between 1,600 and 2,400m in the Glarner Alps of Switzerland, around 90 km south-east of Zurich. The machine and the transformer caverns are situated in Quintner Limestone with an overburden of 400 to 500 m. The 150 m long machine cavern has a height of 53 m and a width of approximately 30 m. The distance between both caverns was increased to 59 m to avoid overlapping plastic zones following the evaluation of geological conditions of the pilot tunnel. During construction it was found that geological conditions are more complex than expected, resulting in displacements varying to a large degree. That was why the design was reviewed by comparing the prognosis with the actual behaviour during excavation of the heading. The rock bolting system with regard to pattern and length was adjusted based on the results of numerical back analyses including sensitivity studies of the rock mass parameters. Additional 3D computations were performed to take account of the numerous intersecting galleries. During excavation of benches, additional rock bolting was provided in specific areas, where deformations continued over some time.

1 Introduction

The demand for sustainable power generation together with the accelerated retreat of glaciers and the predicted change of rainfall regimes requires Switzerland to economize its water resources. Underground pumped-storage plants supply valuable peak electricity while minimizing the impact on the country's natural heritage and water consumption.

The power stations Kraftwerk Linth Limmern (KLL), owned by the Linth Limmern AG in Glarus, were built between 1957 and 1968. From a catchment area of 140 km^2, the power stations produce about 460 kWh per annum. By virtue of their pumping capability, however, their significance in providing peak-load energy across Switzerland is much greater. The project Linthal 2015 combines an upgrade of the existing power stations with a high-capacity pumped-storage plant. A new underground facility will pump water from lake Limmern 630 m back up to lake Mutt. This will boost KLL's output from the current 450 kW to 1,450 kW, a performance on par with the Cleuson Dixence hydro-power scheme.

2 Power plant overview

The four pump turbines are housed in a machine cavern, separated from the transformer cavern (Fig 1). The machine cavern has an internal length of 150 m, a width of 31 m and a variable height of up to 54 m. The side walls curve slightly inwards to obtain a better stress distribution in the rock. The shorter and smaller transformer cavern has vertical side walls.

For details see e.g. Jenni et al. (2010) and Börker et al. (2010).

3 Geology and rock properties

3.1 Regional and site geology

The caverns are located in the Quintner and Tros limestone formation, which in general is to be regarded as offering favourable tunnelling conditions. Nevertheless, schistosity, cleavage planes and weakening zones adversely affect the overall conditions.

In 2007 a horizontal exploration gallery was driven through the planned position of the machine cavern. In several side galleries the orientation and persistence of discontinuities was registered. Based on the findings from surface mapping, boreholes and exploration galleries, the main caverns were oriented perpendicular to the dominating K1 joint system.

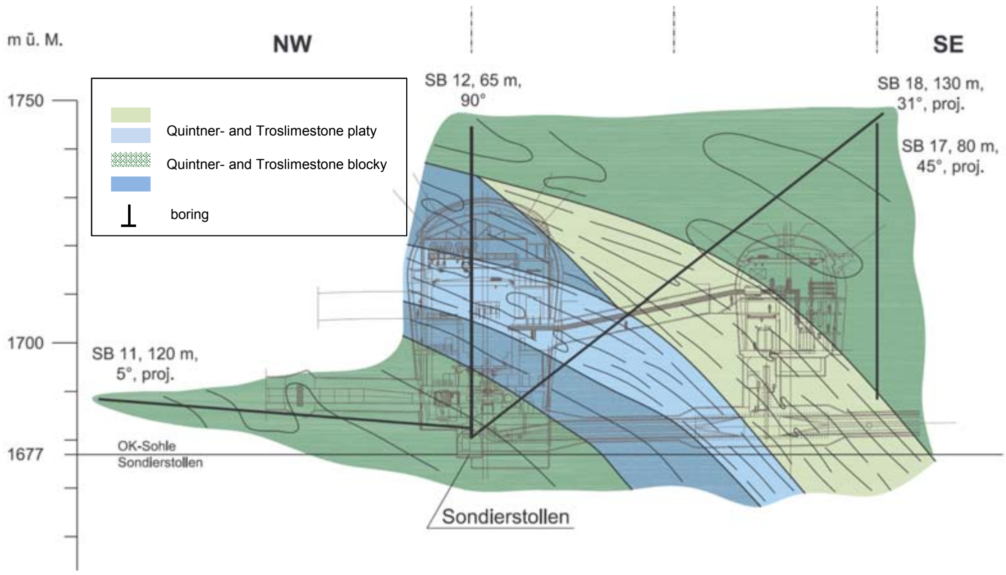

Figure 1. Typical geological cross section of main caverns (basic design with 39 m cavern spacing)

3.2 Geotechnical characterization

Based on primary stress measurements using the Hydrofrac tests in vertical boreholes, it was found that the maximum horizontal stress is oriented oblique to the longitudinal axis of cavern. For calculations the following horizontal stress parameters were used: $k_{0,\ transversely} = 0.4$ and $k_{0,\ longitudinally} = 0.7$.

3.3 Rock mass properties

The mean and pessimistic values as predicted by the geologists were converted into workable design assumptions through the global strength index (GSI)

The Hoek-Brown criterion was used as basis for estimating the rock mass properties.

Table 1. Input parameters for HB failure criterion – Quintner /Tros limestone

rock mass condition	UCS [MPa]	mi [-]	E [GPa]	GSI [-]
blocky	80	10	50	70/55 (*)
schistose	50	10	25	50/40 (*)

(*) taking strain softening into account

Based on these inputs the following Mohr-Coulomb parameters were derived:

Table 2. Rock mass parameters using the Mohr Coulomb failure criterion

Rock mass condition	c' [MPa]	φ' [°]	ψ [°]	E [GPa]	ν [-]
blocky	3.0 / 1.5	47 / 40	17	20 / 10	0.25
schistose	1.3 / 1.0	36 / 33	11 / 8	12 / 6	0.25

x / y: peak value / residual value

The two main caverns are situated in predominantly massive/blocky limestone of the Quintner formation. Between the basic design and the preparation of the tender documents, additional laboratory and dilatometer tests revealed that the Quintner limestone in fact exhibits a higher elastic modulus but partially considerably lower compressive strength. Moreover, a schistose zone was found to partly intersect both caverns (Marclay et al. 2010).

Using the Hoek-Brown failure criterion, the values of Table 2 were derived for the purpose of analysis, including a drop from peak to residual strength.

4 Cavern design

4.1 Layout

The arched roof provides more stability margin in the rock above the cavern. The machine cavern side walls are slightly curved in order to avoid high tensile failure zones in order to reduce support requirements (see Saurer et al. 2010).

Transformers are located in a separate cavern parallel to the machine cavern. A critical design element is the width of the rock pillar separating the two caverns, which is intersected not only by the tailrace galleries, but also by several access and cable galleries.

4.2 Rock mechanical models

Discontinuum and continuum aspects were treated in separate computational models. The size and mobility of key blocks was assessed in 3D e.g. with the software Unwedge (Fig. 2a). The extension of failure zones was studied for various combinations of rock properties and lateral pressure coefficients in a 2D plane strain model with FEM software (see Fig. 2b). The sensitivity to boundary conditions, primary stresses and angle of dilatancy was also investigated.

The effects of spatial stress distributions were checked in several local 3D FE analyses, in particular at the cavern face walls, and in one 3D model encompassing the full cavern system (see Fig. 2c).

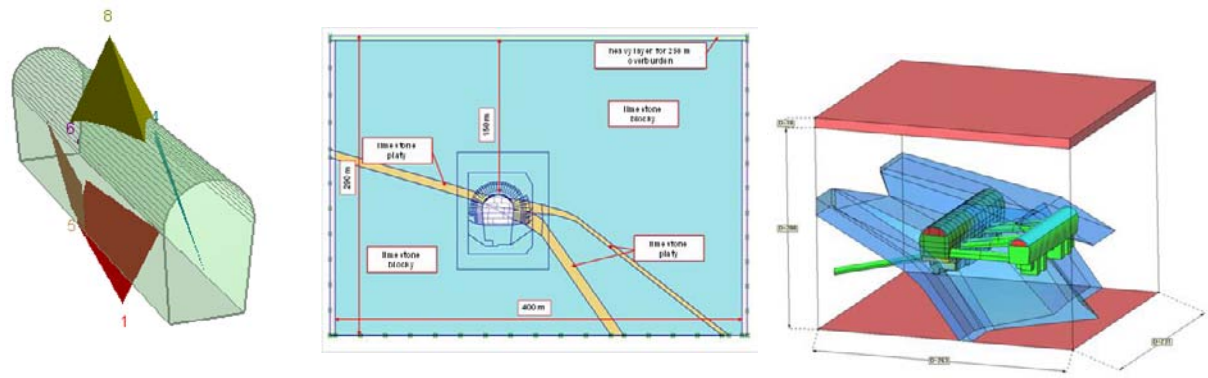

Figure 2. Typical computational models for the cavern design

The caverns are located at a depth of approx. 500 m below ground surface. Creating a FE mesh with the whole overburden height would be computationally inefficient. The specific weight of the layer at the top of the FE mesh is calculated according to the actual overburden. As illustrated in Figure 2(b) and 2(c) the computational boundary conditions are chosen in such a manner as to be able to neglect secondary influences at the boundaries.

The boundary conditions of the FE mesh are as follows: the top face is free to displace, the side surfaces have roller boundaries (horizontal fixities) and the bottom face of the FE model is fully fixed.

In the main 2D analyses the rock mass was modelled with 15-noded triangular elements. In refining the isotropic and homogenous analyses during basic design, a platy-schistose weakness zone was considered and the following constitutive models were applied to simulate more realistic rock mass behaviour:

- transverse anisotropic behaviour using the Jointed-Rock model
- isotropic behaviour using the Mohr-Coulomb model with/without strain softening
- isotropic behaviour using the Hoek-Brown model with/without strain softening

4.3 Design development and process

Due to the fact that the process of stress redistribution is associated with progressive failure of rock mass, the plastic zone or maximum mobilization of strength is adequate to illustrate the pillar stability between caverns. As a design rule, this zone shall be kept as small as possible both as regards tension and compression. Fig. 3 illustrates the results of analyses in which the distance of the caverns has been varied.

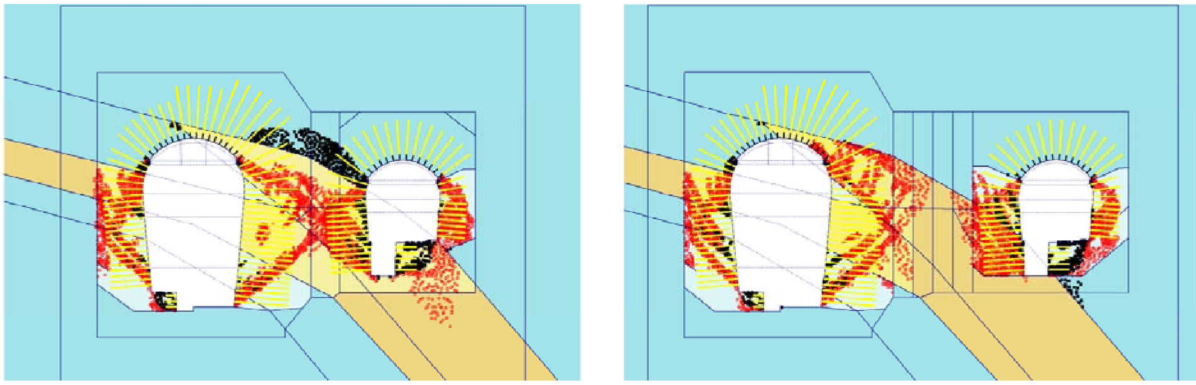

Figure 3. Development of plastic zones – cavern axis distance (62 m versus 82 m)

The analysis revealed that the failure zones of both caverns overlap for a 39 m wide pillar (cavern axis distance of 62 m), even when the rock bolt pattern was intensified and the length of bolts increased to 16 m. By stipulating that the wall displacements of the transformer cavern should not increase the wall displacements of the previously constructed machine cavern by more than 10%, it was decided to increase the spacing of caverns by adding 20 m.

As can be seen from Figure 3, the rock bolts – chosen to a diameter of 30 mm with a pattern of 1.7 m × 1.7 m and a length of 8 m – act as "floating reinforcement" within the failure zones at the walls of the machine cavern.

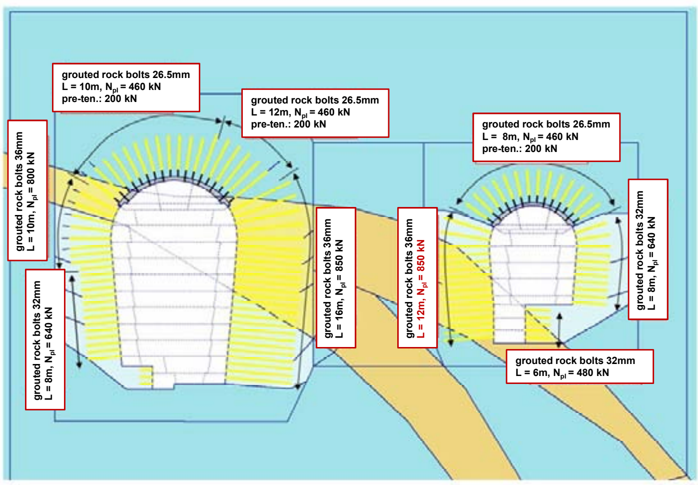

Figure 4. Optimized support system – cavern axis distance 82 m

4.4 Excavation method and support system

A central 6×6 m heading was excavated followed by enlargements of both sides to the full cavern width. Excavation of both cavern headings of the machine cavern and the transformer cavern over full length is followed by installation of cast-in-place concrete arches. Inclined haunches are provided for practical reasons (see Fig. 5). The cranes which are required for installation and operation are supported on beams. The forces acting on the beams are transferred by rock bolts into the surrounding rock.

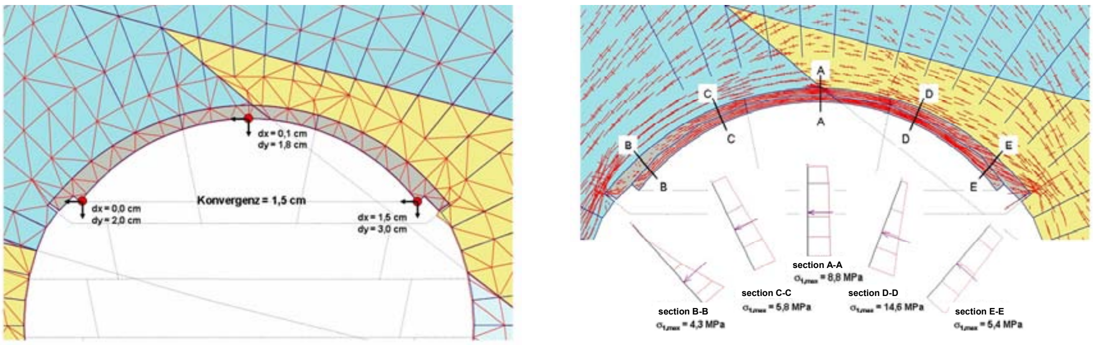

Figure 5. Concrete arch roof design – machine cavern

Subsequent excavation of benches is accomplished by 5 m inclined central cuts. In this stage, the side walls are still protected by 5-7 m wide remaining berms, which are excavated in 3 m advances followed by immediate installation of 10-16 m long grouted rock bolts with a slight prestress to reduce slack. The pattern depends on the specific ground conditions and was coarsened from an original pattern of 1.5 × 1.5m to 2.0 × 2.0 m. The optimized support system, resulting from key block and 2D FEM analysis, is illustrated in Fig. 4. The 2D FE calculations, which determined the support elements, have been checked by 3D FE calculations (see Fig. 6) in order to take into account:

- validity of boundary conditions of 2D FE calculations along the cavern axis
- stabilizing influence of cavern faces on side wall deformations
- effects of adit intersections
- impact of the drive cavern at close distance

Expected cavern displacements and deformations along extensometers for the various excavation stages have been summarised to allow validation of assumptions.

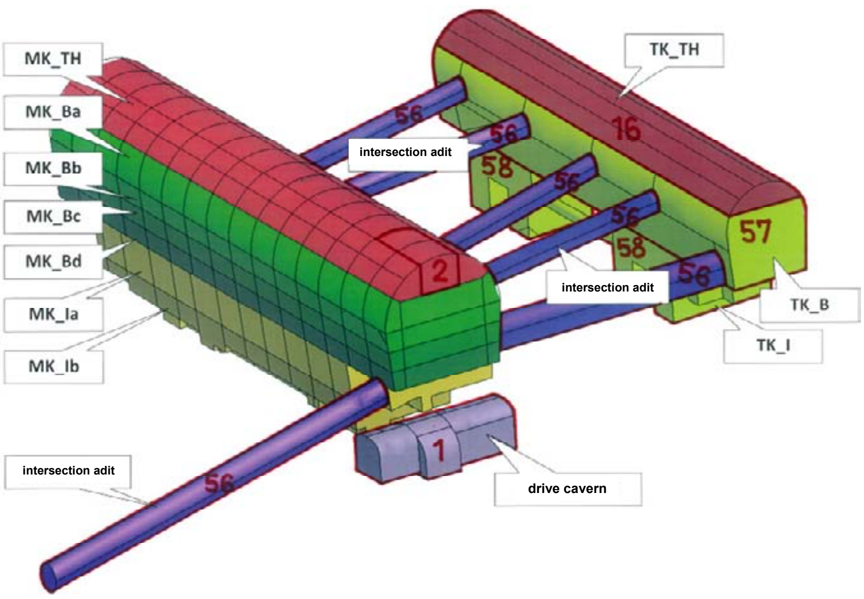

Figure 6. Full 3D FEM modelling (excavation body visualized)

Also the cavern face walls were investigated by 2D FEM calculations with cavity support forces to approximate the spatial stress distribution (see Wachter at al. 2011). The mutual influence of the cable car power house ("drive cavern" in Fig. 6) was investigated in a local 3D model. In addition, a full 3D model was built to check the validity of boundary conditions and the stabilizing effect of cavern faces on sidewall deformations, the effects of adit intersections, and the influence of the spatially dipping weak zone (see Fig. 2c) on the wall deformations.

Figure 7 compares the plastic zones of a local 3D model (with hybrid brick elements and rock anchors) and the full 3D model (tetrahedral elements, rock anchors not modeled). The results were found to be remarkably close.

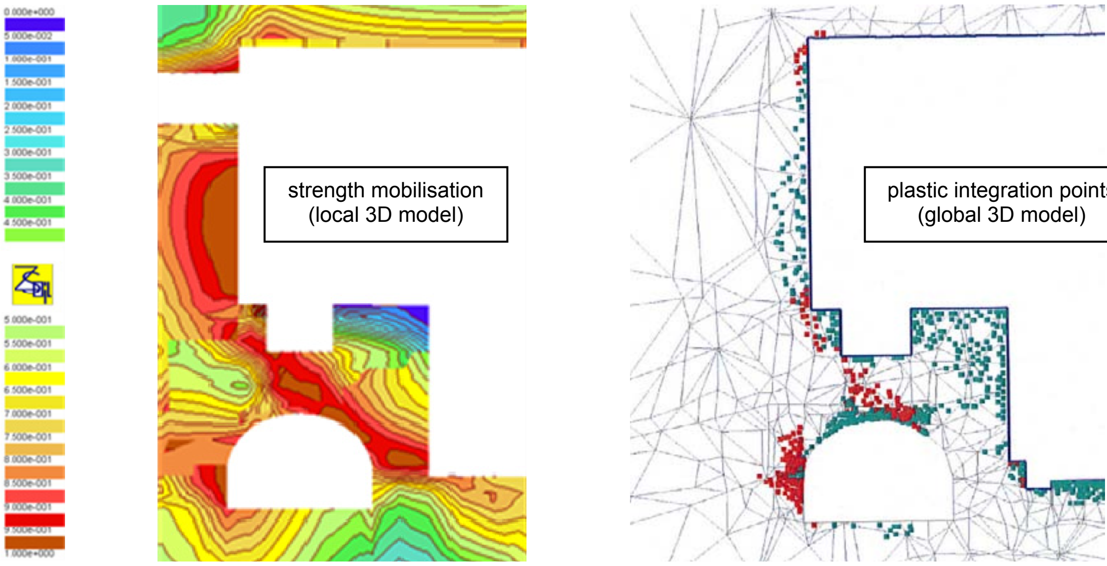

Figure 7. Comparison of different models for the interaction of the machine and the cable car cavern

5 Construction experience

5.1 Geological findings during excavation

During bench excavation it was found that the platy-schistose zones, in a complex configuration, intersect in unfavourable orientation the side wall of the machine cavern next to the transformer cavern. Based on the geological documentation, a revised model for stratification was derived (see Fig. 8).

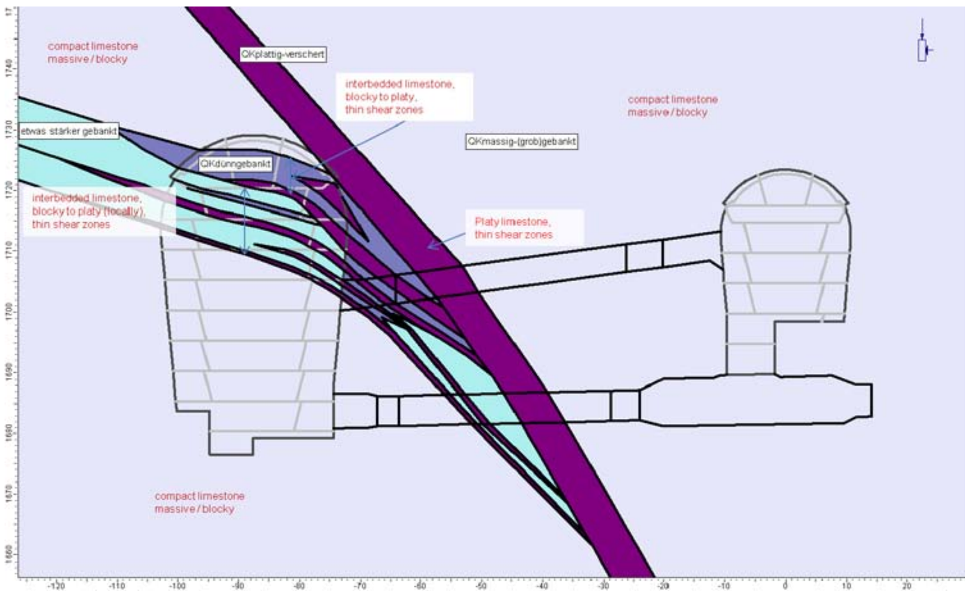

Figure 8. Refined model of the weak zone as updated during excavation

5.2 Geotechnical measurements

During construction, geotechnical monitoring was carried out to verify the support (i.e. observational method). Displacement monitoring together with series of long extensometers in the same section provided detailed result in online transmission. The distribution of cavern wall displacements for a critical section in the final excavation stage is shown in Fig. 9.

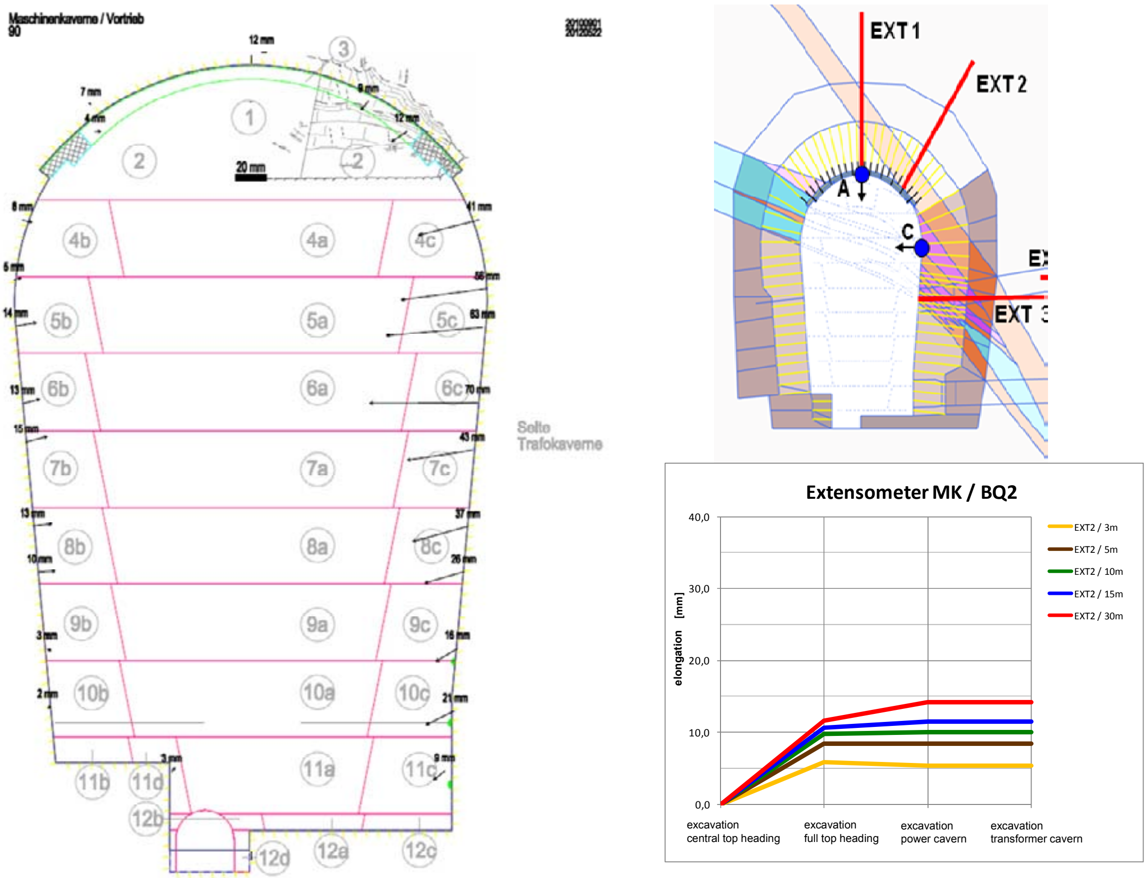

Figure 9. Side wall deformation data of the critical section

5.3 Design adaptations

When the excavation of the machine cavern was completed to about 2/3 of the height, displacements of sections between Tm 70 and Tm110 did not decrease as expected and cracks appeared in the shotcrete. To ensure stability of the side wall in this stage, the standard rock bolt pattern was intensified in this area.

Back analyses were initiated to determine the safety margin and to evaluate rock loads to be applied to the inner (final) cast-in-place concrete lining. The updated geotechnical model is based on the available geological information between Tm 70 – 110. Using the Hoek-Brown failure criterion, the values of Table 3 were derived by back of analysis.

Table 3. Adopted rock mass parameters using the Mohr Coulomb failure criterion

Rock mass condition	c' [MPa]	φ' [°]	ψ [°]	E [GPa]	ν [-]
massive/blocky	3.0 / 1.9	47 / 43	17	25 / 15	0.20
platy / schistose	1.5 / 1.0	37 / 35	12 / 8	10 / 5	0.25

x / y: peak value / residual value

The FE back analysis confirmed that the excavation of the machine cavern is sufficiently stabilized by the support measures installed. Deformations measured could be reproduced by calculations which took into account variations of geological conditions.

Due to the additional rock bolting carried out (final anchor support system in Fig. 10) the displacement increments in the critical areas decreased with time, and effects of consecutive excavations stages were in the range of expectations.

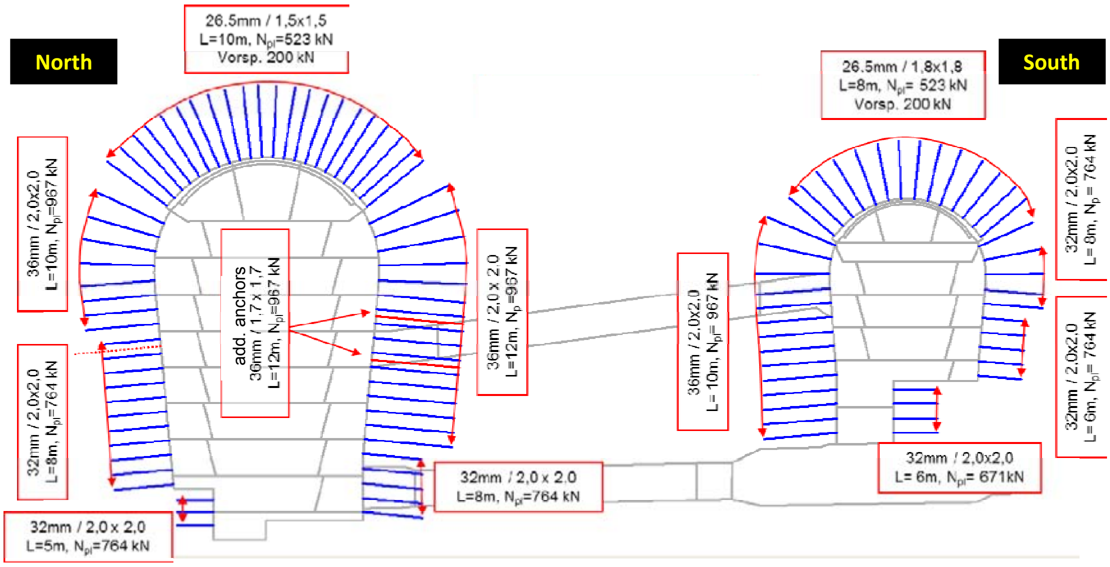

Figure 10. Final anchor support system

6 Conclusions

During construction of the Linth-Limmern main caverns it was found that the geological conditions were much more complex than expected. In a first step the design was optimized after excavating the headings of both caverns. During excavating the bench unfavourably oriented schistose planes resulted at one side wall in displacement rates which did not diminish as fast as expected and exceeded the previously defined warning values. Back analyses were undertaken to check safety margins, and additional rock bolting of critical areas was ordered. Finally back analyses were used to determine loads acting on the final lining when rock bolts are deteriorating.

The interpretation of data according to the observational method along with back analyses was the main key to achieve the goal of an appropriate design validation process.

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