The Renewal of the Pressure Shaft for the High Head Hydropower Plant Kaunertal in Austria

Part 1: Project Overview and Design Criteria

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Abstract

A new steel lined pressure shaft and a surge tank is constructed for the existing Kaunertal high head hydropower plant. The inclined shaft with a diameter of 4.3 m is approx. 1,430 m long and is designed for a pressure head of 100 bar. The steel lining is fully embedded and installed inside the precast concrete segmental lining, which was earlier erected with the tunnel boring progress. Steel design criteria take into account that the internal pressure is shared between the pipe steel and the rock mass according to the stiffness ratio of lining and rock mass. In addition to the demanding design criteria, safety considerations were taken into account, which triggered the development of purpose tailored steel material to be used in the Project. An overview to the Project, which is implemented in the years 2012 to 2015 and the design criteria for the steel lined shaft are presented in the paper.

Project Overview

The Kaunertal hydropower plant was constructed by TIWAG – Tiroler Wasserkraft AG in the years 1961 to 1965 as a highhead storage plant. With its power of 390 MW and a regular

Figure 1: Project Overview

annual energy production of 660 GWh, it was the most powerful hydropower plant in Austria at the time. A 13 km long headrace tunnel followed by the 1.6 km long inclined pressure shaft with an internal diameter of 3.30 m to 2.85 m (maximum gross head 895 m, generation flow quantity 52 m³/s) is situated between the Gepatsch reservoir and the powerhouse at Prutz.

The renewal of the steel lined pressure shaft (Fig. 1) is necessary as a result of the heavy hydraulic loading from power station peak operation and due to the fact that parts of the pressure shaft were constructed in a then unknown landslip and have since been subjected to additional loading from creep movement of the rock mass. The design and sizing of the new pressure shaft and the surge tank take into account a planned expansion of the Kaunertal hydro power plant to twice the nominal flow quantity which will be implemented in a future project state.

The Project is geologically located in the “Engadiner Fenster”. The rocks can be categorized into the two geological units “Grey Bündner Schist” and “Variegated Bündner Schist”. The rocks of the Engadiner Fenster are formed by an extremely ductile tectonic process. They are strongly folded with magnitudes in a range of cm to dm and form very close-standing, waved and foliated planes. The grey Bündner schists are a sequence of a close intercalation (cm) of limestone phyllites and black phyllites; the variegated Bündner schists are a sequence of an even closer intercalation (mm) of limestone and black phyllites, with inclusions of chlorite-sericite-phyllites, dolomites, limestones and gypsums in strongly variable quantities and thicknesses. An extensive programme of site investigation was carried out with several cored boreholes. Samples were taken from the cores and tested for their rock mechanical properties. Radial press tests, which had been carried out in substantial numbers during the construction of the existing pressure shaft were used to determine the stiffness of the rock mass and hence the bedding of the steel lining.

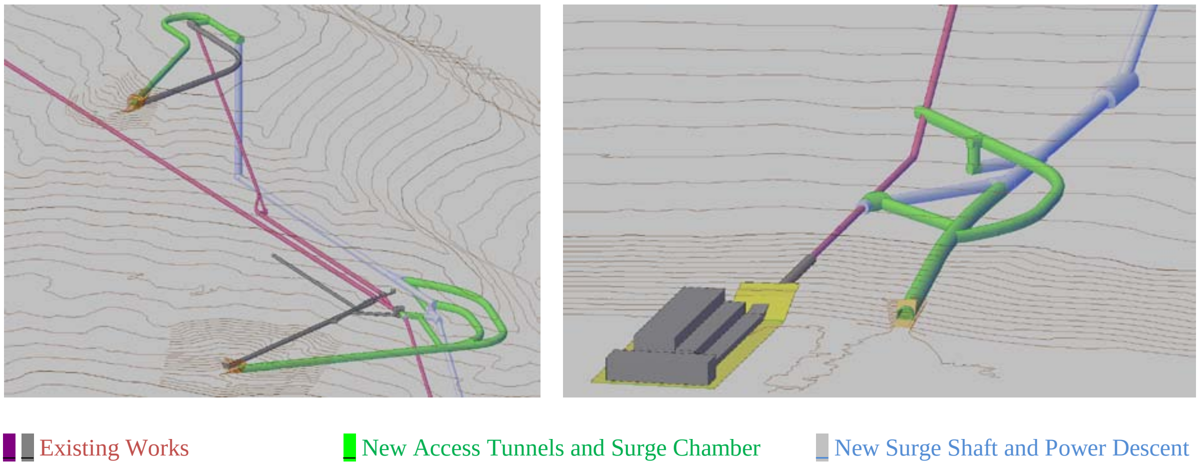

Figure 2: Underground Works Burgschrofen (l.) and Prutz (r.)

Starting from the connection of the pressure shaft to the headrace tunnel in Burgschrofen, the new alignment of the power descent runs in a good 20 m long connection pipe between the existing and the new pressure shaft. The straight length of the inclined 4.3 m diameter shaft is 1,430 m at a constant fall of 60 % until it reaches the penstock tunnel at the lower 30° pipe bend in the shaft base cavern (Fig. 2). The new penstock tunnel is divided into a 180 m long section (4,300 dia.) and an 80 m long section (3,100 dia.), which joins the existing penstock about 200 m before it reaches the powerhouse Prutz. A 30 m long section (3,100 dia.), which is shutoff with a blind cover, branches off for connection of a future second powerhouse. With the exception of connection points, the entire steel lining is backfilled with concrete and embedded in the rock mass.

The new surge tank is arranged as a regulated two-chamber surge tank. The maximum surge level is similar to the existing system at 1,785 m. The new and existing parts of the surge tank upper chamber are lined with shotcrete and hydraulically connected through a 20 m long connection tunnel as well as through the new portal structure. The surge tank riser shaft is the hydraulic connection between the upper and lower chambers of the surge tank and has an internal diameter of 6.3 m. This 150 m deep shaft is waterproofed by a plastic membrane and lined with formed concrete. At the foot of the riser shaft, a jet and a steel lined 90° bend form the transition into the surge tank lower chamber. The surge tank lower chamber has an internal diameter of 5 m and is 435 m long. The waterproofing is provided by a steel pipe (5,500 dia.), which is lined with a cast in-place concrete ring designed to resist the external pressure loading. The surge tank lower chamber connects to the branch pipe in the headrace tunnel with a tapered 70° bend.

Construction of the Works

The documentation was handed in to the authorities in March 2011. With the tendering being carried out in parallel to the approval process, work stated one year later with the legally binding approval. The intended construction period of four years requires a condensed construction schedule, with about 1.5 years for the main excavation works and the same time for the installation of the steel lining. In the remaining fourth year, corrosion protection and finishing works at the portal are envisaged.

Figure 3: TBM-DS (l.) and segmental lined shaft (r.)

The first construction work to be carried out is the adaptation of an existing haul road as site access to the Burgschrofen area to enable most traffic to bypass the villages of Prutz and Fendels. The access tunnels and the surge tank chambers are driven by sequential blasting, with rock bolts, mesh, shotcrete and lattice arches being provided as support. The pressure shaft is bored with a Double-Shield Tunnel Boring Machine (TBM-DS) at an excavation diameter of 5.54 m and the excavation is supported by a hexagonal precast concrete segmental lining system (Fig. 3). In parallel to the boring the pressure shaft, the surge tank riser shaft is sunk in full profile by drill and blast, and the consolidation grouting work is carried out in all the sequentially driven headwater routes. The grouting of the rock mass around the pressure shaft is carried out from grouting platforms after the breakthrough.

After the completion of excavation, work starts in May 2013 on the installation of the steel lining in the surge tank lower chamber at the bend into the riser shaft. Installation, testing and concreting are carried out simultaneously in the penstock gallery, the pressure shaft and the surge tank lower chamber. The steel sheets for the pressure shaft are rolled in the factory, formed into 6 m long pipes, transported to the site, welded in the assembly hall, delivered as 12 m long pipe sections through the Access Tunnel Burgschrofen and lowered into the pressure shaft. In the shaft the assembly sections are welded with assembly splice welds using the WIG narrow-gap-process and back-filled with concrete section by section. Heat treatment for stress-relief is not considered necessary in the pressure shaft or the penstock gallery for a steel lining thickness less than 50 mm. It is anticipated to limit heat treatment to selected partitions of the branch pipes in the assembly hall. Access tunnels are hence designed to a size that branch pipes can be placed in one piece to avoid heat treatment on site.

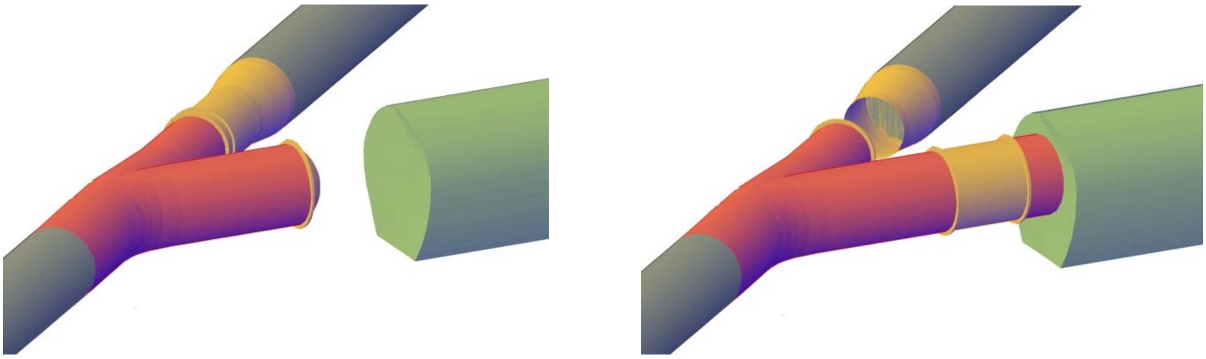

Figure 4: Phase 1 (l.) and Phase 2 (r.) connection to the existing system

The main works (Fig. 4, Phase 1) to prepare the connection to the existing system in Prutz and Burgschrofen takes place during a five month operational stoppage in the first half of 2014. After the steel lining assembly, the entire pressure shaft is filled for a static test. Finally the interface between the steel lining and the concrete fill is grouted with high pressure. Another five months are planned for corrosion protection before the new pressure shaft is connected to the existing system with a removable pipe section in a rapid action (Fig. 4, Phase 2) and put into operation. The old surge tank lower chamber and riser shaft is backfilled and the portals of the access tunnels are completed.

Steel Lining Design

Steel lining design for straight embedded pipes is based on plane pipes tightly embedded in the rock mass. The internal pressure in the pipe is shared between the pipe steel and the rock mass according to the stiffness ratio of lining and rock mass [1]. Such steel lining design requires that the gap between steel and shaft wall is back-filled with concrete and grouted.

The dimensioning of the steel lining is defined according to the k-factor-concept $\sigma_d = k\ \sigma_y$ (factored yield strength) on an infinite length of steel pipe. The authorities require a k-factor of $k = 0.6$ for embedded pipes and σ_y the yield strength defined as the steel material characteristics $R_{p0.2}$ or 0.90 R_m whichever is smaller. For the rock mass, the stiffness of $V_f^* = 3840$ MPa ("grey Bündner schist") and $V_f^* = 1280$ MPa ("variegated Bündner schist") are found the calculated representative values. To limit the rock mass contribution in restraining the internal pressure, k = 0.9 has to be satisfied even without taking the beneficial reaction of the rock mass into account ($V_f^* = 0$ MPa). A rock mass contribution for bearing the internal pressure in the order of 30% is hence considered at maximum.

External ground water pressure and grouting pressure is analysed according to the design concepts and formulas of Amstutz/Jacobsen [2] and [3]. A design factor of 1.5 is defined by the authority. The tolerances of the lining are taken into account with an initial gap of j = 0.0003 r and a non-circularity (50° template) of u = 5 mm. Tolerable grouting pressure is determined as a result of the analysis for j = 0.001 r.

For embedded pipe bends the same principles are applicable in circumferential direction as for the straight embedded pipe. Additional stresses at the connection of polygonal pipe sections in the bend are considered according to Wieser/Green/Emmerson/Greiner [4]. Branch pipes whether embedded or not are analysed without taking the beneficial contribution of the rock mass into account. The steel thickness is determined for the self-supported case, which is capped on all sides and the particular site arrangement is modeled to find potentially worse loading conditions of the more realistic embedded case. Individual k-factors are defined for different combinations of membrane-, peak- and bending stresses in the branch pipes. Special regard is given to pipe accessories like pipe rings to improve buckling, openings and auxiliary steel plates for maintenance access, survey and grouting which are installed in the steel lining in substantial numbers. The shape and size of these openings is optimized using analysis and test results by recently performed research at the Technical University of Graz [5].

Dynamic loads generated by power plant operation are considered according to the Eurocode. The specified amplitude of 5 bar at a frequency of 8×10^7 load cycles in 100 years as derived from operation history turns out to be the decisive load case for many partitions of the steel lining and pipe accessories. The design requirements for the Project are normally met in case the welding detail and weld treatment satisfies category 112 according to EN 1993-1-9.

Steel Material Specification

It is noted from experience with existing steel lined pressure shafts in the area of TIWAG responsibility, that stringent ductility criteria and substantial uniform elongation of the steel material is of indispensable advantage. Unfortunately ductility criteria are not implemented in the steel lining design directly, since material performance is normally measured by high strength at little deformation. Plastic steel deformations are not utilised or ignored in the design. To push the limits of application and to save costs, steel materials are available, which take high stresses beyond 700 N/mm^2 in an elastic state but loose performance rapidly once they turn plastic. According to (Fig. 5) it is obvious the higher the design steel strength ($R_{p0.2}$) the lower the tolerable uniform elongation (A_{gt}). This trend is challenged however by the following safety considerations for a pipe embedded into the rock mass:

- The larger the expansion of the steel lining the higher the resistance of the rock mass regardless, if the steel continues to take more load (elastic deformation) or not (plastic deformation). In the plastic state other criteria start to govern steel material performance and watertightness criteria. (joint bridging criteria, fracture toughness, etc.)

- Non-problematic behaviour at undefined bedding conditions
- Wide stress redistribution in the region of overstressed partitions and no concentration of stress. In particular concentration of deformation at welds has to be avoided (overmatching).
- Slowly developing cracks which can be detected before failure of the system (leakage before breakage)

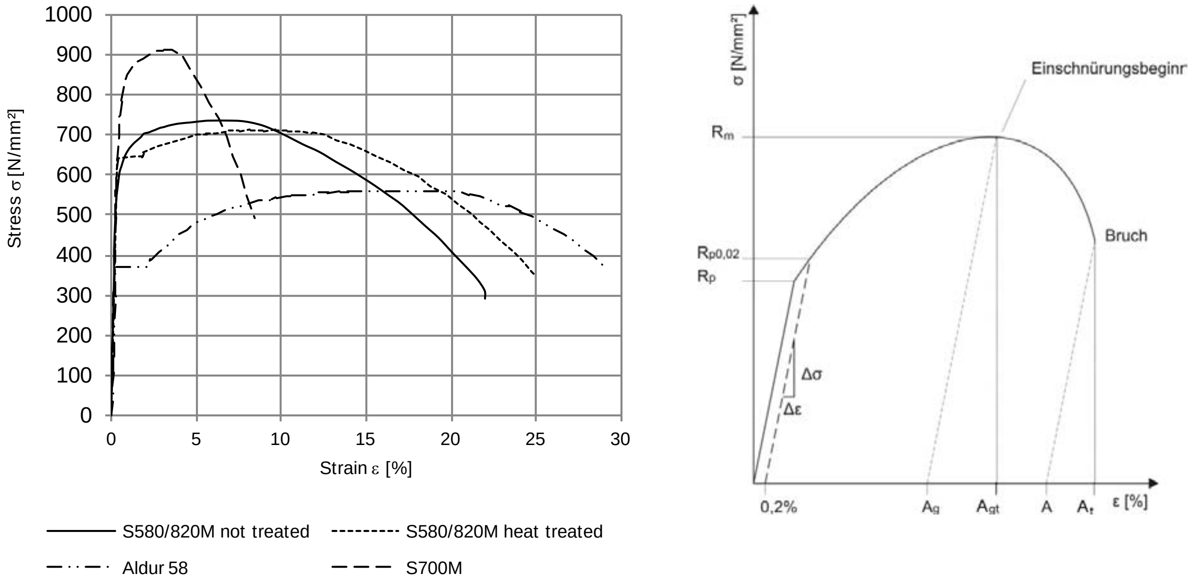

Figure 5: Typical stress-strain curves for pipe steel materials

Notwithstanding the demanding performance criteria for the Kaunertal Pressure Shaft which are indicated by a max. tensile hoop force of PxR = 21500 KN, the steel material specification is aiming to

- define the design steel strength (min. $R_{p0,2}$) as low as economically practicable
- limit the potential steel strength (max. R_m) to match welding materials
- push elongation at tensile strength for to improve deformation capability
- define performance criteria at break (toughness at low temperature, fracture mechanics) to avoid brittle failure

For all load scenarios standardized ideal material behaviour is normally considered in the design of pipes and welds. This is accepted in the Project for “normal strength materials” because of the generally high ductility (Fig. 5, former penstock steel Aldur 58 and similar). Driven by economical benefits and by the need to limit steel panel thickness, steel of higher strength is however preferred. The high performing steel and welding materials require detailed analysis and testing to determine if selected materials fit into the Project requirements. Deficits implemented during the pipe manufacturing and welding process are regarded in particular. Therefore a comprehensive laboratory and on-site programme is adopted for testing and documentation, which includes standard laboratory tests, toughness tests and 100% TOFD and Phased Array ultrasonic testing of welds.

During the bidding process and before contract award to the steel lining supplier extensive suitability tests were carried out on sample pipes by the prequalified bidders to select steel and welding materials. It was noted, in the tests that steel materials having high yield strength did not perform satisfactorily in the ductility tests (Fig. 5, S700M – boric alloy). Also was the demanded overmatching (i.e. R_m of welding material higher than max. R_m of pipe material) difficult to achieve for welding materials in combination with high performance steel materials. The tolerable steel strength was therefore limited to a maximum yield strength of $R_{p0.2}$ = 620 N/mm^2. After additional testing during the Project a purpose designed product based on a thermo-mechanically treated pipe line steel with a design yield strength of $R_{p0.2}$ = 580 N/mm^2 was selected for the majority of the pressure shaft and penstock sections. If necessary the steel material is conditioned by thermal treatment to match the demanding specification. Within the given design criteria it is such expected that the majority of the steel lining can be provided economically by the steel quality S 580/820 (Fig. 5) and lower with a plate thickness of 25 – 50 mm. Only selected parts like branch pipes and flanges require a substantially thicker material.

Conclusion

The renewal of the pressure shaft for the Kaunertal Hydro Power Plant is a particularly challenging project for its large size, high stress condition and situation in difficult geology. Means have to be adopted, which reach beyond standard practice to satisfy exceptional project requirements:

- Inclined shaft excavation with a Double-Shield Tunnel Boring Machine (TBM-DS) and the excavation supported by a precast concrete segmental lining system
- Connection to the existing system in two phases to assure that no water loss takes place in the reservoir
- A steel design for the shaft lining which utilises the beneficial reaction of the rock mass for embedded pipes
- A steel material specification which allows economical lining thickness while demanding maximum ductility, exclusion of brittle failure and capping of tensile strength to assure overmatching for welds.

The matching of all these challenges is facilitated by a fruitful collaboration between construction contractor, steel provider, steel manufacturer and owner, who are responsible for a practicable design, the timely production and a well organized site management.

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