Retrofitting the Sylvenstein reservoir

The Sylvenstein reservoir – Bavaria's oldest state-run reservoir – was erected between 1954 and 1959 and is located about 60 km south of Munich. Originally 45 m high, the earth-fill dam with an impervious core impounds tributaries from the 1,100 km² catchment area of the Isar, Walchen and Dürrach rivers. The dam protects people living in the Isar valley - especially inhabitants of Bad Tölz and the greater Munich/Landshut area – against flooding, ensures adequate minimum water flow in the Isar River, which has been narrowed by water withdrawal, and delivers green hydropower. Following a detailed inspection essential retrofitting work has been carried out since 1995 without any interruption of dam operation.

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1 Reasons for the retrofitting work

The flood control efficiency of the Sylvenstein reservoir was reviewed after more than 25 years in operation. The design scenarios HQ100 and HQ1,000 that applied at that time were ascertained based on historic flooding events and synthetic precipitation with varying return periods (50 to 1,000 years), durations (24 to 96 hours) and geographical distribution.

At that time, hydrological safety (against dam overflow) was reviewed using the design inflow of a 1 in 1,000-year flood event in accordance with DIN 19,700 (1986 edition), whilst taking account of a limited reservoir release (n-1) rule under DIN 19,700. In this instance, this meant the failure of a 370 m³/s bottom outlet. The review also looked at the protection of downstream settlements against HQ100 using the existing flood retention capacity and while complying with maximum river flows in Bad Tölz (450 m³/s) and Munich (900 m³/s). The findings revealed shortcomings in maximum reservoir release and in the reservoir's flood control storage in the event of extreme flooding.

Further adjustments were needed in the wake of changes in water availability in the catchment area for the upper Isar and due to problems at the 40-year-old hydropower station, which was in need of repair, and also serves as fine-regulating facility for raising low water levels in the Isar River.

The following measures were needed for retrofitting purposes:

- Constructing an additional spillway with a capacity of 400 m³/s to ensure the dam's hydraulic safety (completed in spring 1997).
- Raising the height of the dam by 3 m and increasing usual flood control storage capacity by 20 million m³ to protect downstream communities against up to 1 in 100-year flood events (completed in summer 2001).
- Building a new hydropower station (3.8 MW capacity) to undertake fine-regulating of low water discharge into the Isar River (commissioned in June 2000). The 50-year-old underground power plant was subsequently replaced (completed in October 2004).
- Replacing all hydraulic steelwork components (scheduled for completion by June 2021).

Kompakt

- Retrofitting the Sylvenstein reservoir by adding another spillway and raising the dam's height by 3 m.
- Construction of a second hydropower station and complete reconstruction of the old power station.
- Replacement of all hydraulic operational steelwork facilities.
- All work took place with the dam continuing to operate.

2 Additional spillway

Favourable geological conditions existed for the new structure on the left flank of the valley upstream of the dam. The intake was located in a small cove to protect against log jams. An outlet tunnel takes a straight line to the ski-jump from the base of the intake structure and casts the jet of flood water into a downstream plunge pool for energy conversion without damage. The spillway was tested using a 1:40 scale model at the Technical University of Munich's hydraulic laboratory in Obernach. The dimensions and exact form of the intake structure, tunnel and ski-jump with a capacity of 400 m³/s were designed and optimised there.

With a total width of 25 m, the intake structure (**Figure 1**) is divided into two weir openings each 12 m wide by a central pillar. A row of columns is placed in front of the intake area to protect against driftwood. After the overflow sill, water plunges into a drop shaft about 18 m deep. The narrow outlet on its front side means that a water column builds in the drop shaft, creating the pressure needed to guide water into the discharge tunnels at high speed.

A column stabilises the turbulent current in the transition section at the entrance to the tunnel. The transition section from the rectangular profile to horseshoe profile was designed as a penstock. At its end, ventilation pipes integrated into the intake structure's front side compensate for atmospheric pressure. The connecting 550 m-long headrace tunnel with a 3 % gradient was designed as a horseshoe profile that was 8 m high and a


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Figure 1: Intake structure for the new spillway


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Figure 2a: New spillway: ski-jump of the new spillway


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Figure 2b: New spillway: first use of the new spillway with 260 m^3/s over the ski-jump on 23 May 1999

maximum of 8 m wide. The wall and floor surface were clad with concrete to reduce wall roughness. At full pressure, speeds in the gallery reach up to 16.5 m/s (60 km/h).

At the end of the gallery, the discharge jet is cast upward over a ski-jump (**Figure 2a**) and ruptured by a concrete wedge for better energy conversion. The stream flies freely up to 35 m into the downstream plunge pool, into which the bottom outlet gallery and the old spillway empty. The ski-jump solution was chosen because a 50 m-long and 10 m-deep stilling basin with a similar effect could hardly have been integrated into the landscape.

Creating the tunnel

The safety of the dam and its unrestricted operation during construction were key factors in selecting the construction method to create the tunnel. Critical vibrations at the tight connection between the dam and rock flanks and nearby operating facilities (bottom outlet and existing spillway) had to be avoided. Therefore, a combined solution was selected for creating the tunnel made up of cutting (Ø 3.50 m pilot gallery) using a tunnel boring machine to pre-reduce stress and blasting technology that preserved the rock (2 stages with spherical cap bar and bench). The tunnel was then clad with a concrete shell about 0.5 m thick at its base and side walls up to a height of 4.50 m. The tunnel roof did not have to be strengthened using shotcrete or anchors due to the compact rock conditions. A drainage system behind the concrete cladding helped to ease the pressure from mountain water.

Intake structure

Work on the intake structure took place alongside tunnel excavation. The pit, which was 32 m long and up to 30 m deep, was created in 2 m sections by blasting into the compact dolomite. Since a main road runs very close to the construction site, work could only be performed with a significant amount of effort to secure the site. The walls of the pit are strengthened with a total of 148 permanent anchors (anchors are a maximum of 25 m long). Work to concrete the 1.50 m-thick floor of the structure could not begin until April 1996 once extremely heavy icicles on the walls of the excavation pits had melted. The rising walls were concreted directly against the bedrock in the lower section up to a height of 4 m. Higher sections of the wall were created with formwork on both sides.

The overflow sill consists of 24 pre-fabricated elements with an individual weight of 6 t. These elements were hoisted through openings in the ceiling of the intake structure using mobile cranes. The look of the finished structure, popularly known as the ‚Sylvenstein Temple‘, is evocative of a traditional Greek structure with its row of columns (Figure 1).

Outlet structure

The ski-jump at the tunnel outlet with an area of about 10 x 13 m^2 was chosen to convert energy at a dam in Bavaria for the first time. The structure is built entirely on bedrock and anchored. The forces created from diverting the jet can be absorbed in this way. The outlet structure's external guide wall was angled by 20° and the inner wall by 35° owing to the peripheral location of the ski-jump compared with the existing plunge pool (Figure 2a). A solid concrete wedge is located in the middle of the jump's edge, which divides the jet stream. This achieves effective energy conversion together with diverting the jet stream. The mathematical force on the concrete wedge is more than 1,000 t at full pressure. All edges of the structure in contact with water are protected by steel profiles encased in concrete due to high flow speeds.

Construction time and costs

Construction began in 1994. About two years passed from the pilot tunnel being driven in April 1995 to the intake structure being completed in spring 1997. The new spillway cost a total of approximately EUR 10.8 million.

The new spillway was first used during Whitsun floods in May 1999, discharging 260 m^3/s (**Figure 2b**).

3 Increasing the height of the dam

Raising the height of the dam by 3 m was confirmed as the best solution in a regional planning procedure, as it safeguards the reservoir's main duties (flood control and elevating low water levels) and minimises interventions into the existing structure and the landscape. This 3 m elevation comprises a 2 m earth-fill banking combined with a 1 m superimposed crest wall (**Figure 3**). Consequently, the flood protection storage that could be managed was increased by 45 % from 59 to 79 million m^3. The official approval of the plan cleared the way for the planned increase in the dam's height in January 1997.

It was noted that the impoundment lamella between the current flood control level (763 metres above mean sea level, MAMSL) and the maximum water level (767 MASML) with a storage of 25.9 million m³ serves as retention volume in the event of disastrous flood events (> HQ100) while also acting as a safety valve to protect the dam against damage, overload or destruction (e.g. the bottom outlet gallery failing) in interaction with the spillways. Following a flood wave, the flood control storage must be emptied back to the normal operating level as soon as possible so that it can be made available again for new flood events.

Widening the old dam crest

The embankment dam is a zone dam with a central impervious core and shoulders made out of gravel material. The main road B 307 with a footpath and a strip of parking spaces goes over the 15 m-wide and 200 m-long dam crest. They will be retained after the rebuilding work. At the same time, traffic flow over B 307 had to be maintained during construction work.

Earthwork began in autumn 1997 with a rock-fill on top of the berm on the downstream face in the upper third of the dam. The existing dam crest was widened and space was created to temporarily move the main road using the steepened 1:1.6 dam slope. Excavated rock from the pit of the new spillway that had been stored temporarily and processed was largely used as rock-fill material.

Rebuilding the old spillway

The old spillway had a floating (controllable) sector weir, known as a drum gate, in the intake structure to manage the reservoir. The overflow sill and ceiling structure had been raised (**Figure 4**) to reflect the new maximum water level. The new fixed overflow spill has a wide weir crest with a weir co-efficient of $\mu = 0.55$ for maximum discharge of 200 m³/s to avoid hydraulic overload of the connecting headrace tunnel. This work took place in parallel with the widening of the dam from September 1997 to spring 1998.

Sealing measures

The dam's impervious core was improved in the upper impoundment area and it was adapted to the higher maximum water level with the help of a mixed-in-place (MIP) method. This method entails in-situ soil treatment by drilling with a triple augur and subsequent cement-bentonite mortaring. With an area of 2,100 m², the new cut-off wall in the dam axis traverses the entire dam length up to 12 m deep and was created in about six weeks. Additional grouting holes on the edge areas of the dam ensured a tight connection with the rock abutments.

Crest wall

A 1.5 m high rock-fill dam with a base width of 10 m was created at the dam's edge on the upstream face. This dam serves as the basis for a 1.80 m-high cantilever retaining wall (Figure 4 and **Figure 5**). The wall is concreted in 10 m sections with a water-stop sealing. The base of the wall is sealed to the top of the MIP wall using a slanted loam banking. On the upstream face, the drawn-up and steepened slope (1:1.5) is protected against the impact of the waves with stone packing.

Road modifications

The main roads B 307 and B 13 lead up to the crest of the Sylvenstein dam. The construction work needed to adjust the road gradients to the dam's new height was much less complex with the chosen solution of a 2 m dam banking and a 1 m crest wall than it would have with a 3 m dam banking. Therefore, the length of the ramp on B 13 coming from Lenggries was shorted to about 250 m, thereby avoiding the need to rebuild two arched bridges spanning torrents beneath the dam.

The retaining walls for the road up to 8 m high near the dam, which needed rehabilitation, were changed to the future height and rehabilitated between April and December 1998. The old retaining walls were integrated into the new construction without static overloading using a load-distributing reinforced concrete transition slab up to the middle of the old road and a superimposed retaining wall cantilever.

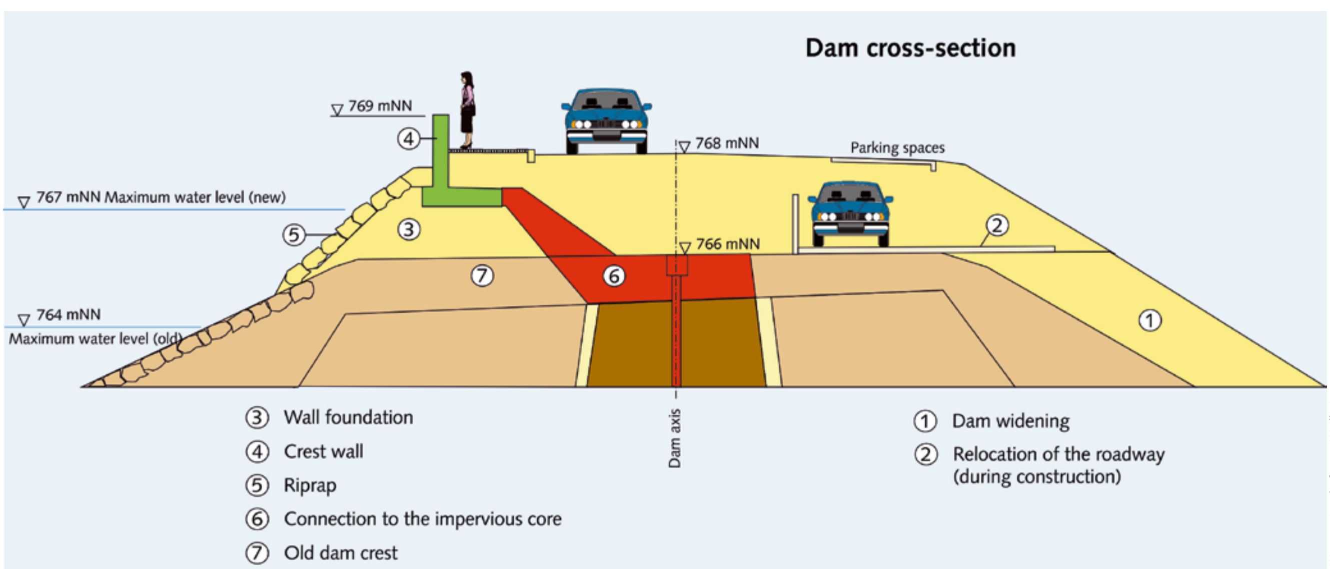

Figure 3: Installation of the intake sill and raising the pillars of the old spillway

Figure 4: Cross-section with the elevated dam crest, widening and sealing

Figure 5: Construction of the crest wall and banking for the elevated section of the dam

Figure 6: Reinstallation of individual segments of the overflow sill on the new spillway (after elevation)

Gate shafts in the bottom outlet and operating outlet

Raising the maximum water level from 764 to 767 MAMSL also entailed making fundamental modifications to the gate shafts in the bottom outlet and operating outlet. For instance, access to the bottom outlet had to be adjusted to the new road height and ventilation devices in the free flow tunnel in both gate shafts' winch caverns had to be changed. The entire hydraulic steelwork underwent a general overhaul.

Measuring system

In a first stage, the measuring system at that time was modernised and upgraded for dam monitoring purposes as part of grouting work on the impervious core in 1987/88. The second stage took place as part of work to raise the height of the dam. The subsequent installation of another 17 pore water pressure probes in the dam core and in the grout curtain in the bedrock plus another seven observation gauges in the chimney filter meant that the dam now had a dense inspection system. The 47 pore water pressure probes and 61 dam gauges at that time are captured in seven measurement profiles and allow for early detection of any potential changes in the dam and subsoil in connection with the seepage drainage system, if needed.

Modification to the new spillway

The legal proceedings involved in raising the height of the dam were not yet completed when the new spillway was constructed (1994 to 1997). While the floor of the intake structure was already designed to meet future conditions, the height of the overflow sill initially had to be designed for the old flood control level. A design was chosen for its later modification that made it possible to simply raise the overflow sill. For instance, parts of the intake structure's roof slab and the overflow sills were made out of prefabricated concrete elements. After the dam was raised by 3 m, prefabricated slabs of the intake structure´s roof weighing each about 15 t and applied to temporarily close the assembly openings were first lifted up in spring 2000 using a mobile crane. The individual segments of the overflow sill (1 m wide each, weighing approximately 6 t) were hoisted out of the supporting beams and moved sideways. The overflow sill is constructed as a hollow body consisting of prefabricated sections which are solely screwed into the supporting beams from the inside. The two supporting beams were heightened with concrete by 3 m after clearing. The overflow sill sections were then lifted up again, laid and fastened to the supporting beams and sealed (**Figure 6**).

Construction period and costs

The total costs of raising the height of the Sylvenstein dam, including modifications to the operating facilities and main roads, amounted to around EUR 9.1 million. Construction took place between 1997 and 2001.

4 The new hydropower stations

For environmental reasons, the Isar River has been fed 3.0 m³/s of residual water flow in the winter and 4.8 m³/s in the summer since 1990 because of partial reverse flow in Krün. Since then, the Sylvenstein reservoir has received about 123 million m³ more water in an annual average. The decision was made to construct a second hydropower station (Hydropower station II, **Figure 7**) at the base of the Sylvenstein dam after maintenance and repair work at the 40-year-old hydropower station had become increasingly complex and a fine-regulating facility was not available to discharge water for a long period of time during repairs.

The 11.5 m-deep, circular shaft powerhouse (Ø 14 m inside) takes the form of a secant bored pile wall with a pile length of about 16 m. The 70 m-long headrace tunnel (Ø 2.50 m) was designed as a steel pipeline from the branch of the existing penstock in the hard rock zone. A new type of compact axial turbine with an intake capacity of 15 m³/s and 3.8 MW at a head of 13 m to 39 m was selected as a turbine. A total of about EUR 7.7 million was invested in this work between 1998 and 2000.

A vertical axis Francis turbine was installed during the subsequent replacement of the old underground power station. Commissioning took place in October 2004 after about one year of construction. Total costs stood at approximately EUR 2 million.

A total of up to 25 m³/s can be discharged using the replaced underground power station and hydropower station II. At full exploitation of the potential water discharge, maximum electrical capacity stands at 6.4 MW. Annual power generation by both power stations averages 26 million kWh/a. Bayerische Landesk-


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Figure 7: Compact axial turbine at hydropower station II


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Figure 8: Replacement of the hydraulic steel facilities, upper sluice gate in the bottom outlet

raftwerke GmbH operates the hydropower stations with local staff from the Weilheim water authority.

5 Replacement of the hydraulic steel structures

The Sylvenstein dam has two discharge outlets at the level of the lake's bottom – the bottom outlet and the operating outlet – to which both hydropower stations are connected. These two outlets control water discharge from the reservoir. This approach maintains adequate flow in the Isar River throughout the year and guarantees safety along the Isar river to past the Munich metropolitan area in the event of flood.

For tunnels to be inspected, tunnels must be dried out by closing the inspection gates in the tunnel's intake area and must be accessible. So far, these gates have only been able to be moved with the help of gantries and pulleys when the reservoir level is lowered. The process is complicated and protracted and could only be carried out at times when there is low risk of floods (outside the winter months) for safety reasons. This reduction in the reservoir level inevitably involved the loss of stored water for low water regulation in the Isar river.

When the new hydropower stations were constructed, the inspection gate on the operating outlet was also rebuilt in winter 1998/99 so that it can be used at any time without having to lower the level of the reservoir. The inspection gate is moved using an electric cable-stayed hoist with pulleys. A diver locks and unlocks the gate in the park position.

This design has been proven time and again since 1999 and makes tunnel inspections much easier. Therefore, the bottom outlet‘s inspection gate was also replaced by a similarly functioning system in spring 2016 after almost 60 years in operation [3].

The maximum water level is 5 m higher than originally planned today thanks to the dam having been raised in the past. Neither the inspection and sluice gates nor the drive systems were designed for today's possible maximum water level. The hydraulic steel facilities, which was coming close to the end of its life after 60 years in operation, was ultimately put under so much strain during the 2013 flood event when a new record high water level of 762.95 MAMSL was reached that it became necessary to rehabilitate the hydraulic steel facilities soon [4].

Renovation work on the bottom outlet entailed two new 19 m² gates weighing 21 t, which were installed as two-part gates with a modern hydraulic drive in a dry shaft (rather than lifting rods with gear drive in a wet shaft) (**Figure 8**). The operating outlet kept two new 13 m² and 15 t sluice gates in a wet shaft, but also switched to a hydraulic drive. As part of this work, side guide rails, the steel lining and the gate ventilation system are also being rehabilitated and a crane system and stair tower are being installed into the 40 m deep shafts. All electrical components and the access level are now above the flood control level since the dam was raised.

Work was staggered to avoid both outlets not working at the same time. The more powerful bottom outlet was first rehabilitated and then started operating in 2016/17. The operating outlet will then follow after preparatory work in 2018/19. During construction, the planned, but constantly monitored restriction of an outlet may be lifted within a short period of time by clearing the building site.

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Der Sylvensteinspeicher – Nachrüstungen

Die Talsperre Sylvensteinspeicher – Bayerns ältester staatlicher Wasserspeicher – wurde 1954 bis 59 gebaut und liegt ca. 60 km südlich von München. Der ursprünglich 45 m hohe Erddamm mit Kerndichtung staut die Zuflüsse aus einem etwa 1 100 km² großen Einzugsgebiet von Isar, Walchen und Dürrach auf. Die Talsperre schützt die Bewohner des Isartals – vor allem Bad Tölz und den Großraum München/Landshut – vor Hochwasser, sichert eine ausreichende Niedrigwasserführung des durch Wasserableitungen geschmälerten Isarabflusses und liefert umweltfreundlichen Strom aus Wasserkraft. Im Ergebnis der vertieften Überprüfung der Talsperre werden seit 1995 wesentliche Nachrüstungsmaßnahmen unter Weiterbetrieb der Talsperre durchgeführt.

The replacement of the hydraulic steel facilities and drives will make sure that outlets can function without restrictions again in future. The planning and construction costs amounted to about EUR10 million.

6 Summary

The planning, construction [1] and retrofitting of the Sylvenstein dam are a good example of farsighted and successful regional policy. Despite sometimes significant opposition – especially against raising the height of the dam – the responsible water management authorities have taken the necessary steps in a purposeful and consistent manner. Major floods at Whitsun 1999, in August 2005 and June 2013 put the improved protective action of the Sylvenstein dam to the test. At these times, the new spillway and the main elements of the increase in the dam's height were already in place so that the massive flood could be managed in an effective manner and no severe damage occurred in the towns, cities and communities in the Isar valley [2].

Following the creation of an additional 20 million m³ of flood control storage (thanks to raising the dam's height) and the construction of new hydropower stations and the second spillway, retrofitting measures will continue [5] and be completed with replacement and modification of the hydraulic steel components in 2021.

The value of this flood protection structure – which has always been kept in step with the latest technology – cannot be overstated knowing the massive potential for damage downstream of the Sylvenstein dam.

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