Upgrading the Sylvenstein reservoir sealing and inspection system

The Sylvenstein reservoir was brought up to date between 2011 and 2015 after more than 50 years in operation by adding a diaphragm wall to the existing dam and subsoil, as well as a new measurement system for seepage. These additional upgrades are also considered preventative measures against possible impacts of climate change, as the magnitude and frequency of recent flood events imply an expected larger stress on the dam in the future. With a total cost of about EUR 23 million, construction work was co-financed by the European Fund for Regional Development.

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1 Reasons for the upgrade

Since its commissioning in 1959, the Sylvenstein reservoir has provided protection against floods and has contributed to the Isar River regime by supplying water during dry periods. At the same time, it generates green power for the public grid. It has also become an attraction for local people and tourists seeking recreational activities alike.

Between 1994 and 2001, Bavaria's oldest state-run water reservoir was technically updated to the stipulations of the German standard governing dams, DIN 19,700 by constructing a second spillway and increasing its flood control capacity by raising the dam's height by 3 m [3], [13].

The settlement of the dam in the deep and narrow gulch dating back to the Ice Age caused fissures to form in the dam core, which were grouted in 1972 and 1987/88. This grouting, however, also impaired parts of the chimney filter on the downstream face. Ageing problems with the sealing, which had been tempered with bentonite, had already been reported in the 1990s [1].

More recent investigations and test drillings in the dam's subsoil indicated elevated permeability in the dam's foundation area and the in-situ underground sealing. Camera inspections of the old drainage system and hydraulic long-term tests found that seepage was likely no longer entering the seepage collecting basin – probably due to the aforementioned grouting – and free flow from this collecting basin is limited due in part to earlier dam settlement. The network of pore water pressure sensors installed for monitoring purposes also revealed drifting readings at times.

The findings of these investigations and their critical analysis while taking account of DIN 19,700 (2004) made it appear reasonable to add another sealing to the dam core and the subsoil with today's technology and completely replace the seepage measuring system.

The dam, the alluvial subsoil and the neighbouring bedrock were investigated in a drilling campaign in 2009. Seven boreholes going down to a depth of 140 m were first drilled in the area of the dam core. The present, heavily aquiferous valley alluvions (Isar alluvions) are composed of alternating layers of sandy and silty gravel to cohesive soil made out of lake marlstone chalk. Some 700 m of drill core material was initially used to identify shear parameters, friction angles, cohesion, permeability coefficients, grain size distribution and density information for each zone of the dam, the subsoil and bedrock based on the exploratory programme looking at soil and bedrock parameters.

Synopsis

- Proven special engineering methods permit the diaphragm wall and inspection gallery to be created while the dam is operating.
- The installation of the diaphragm wall makes a key contribution towards guaranteeing the dam's fitness for use and thus for reliable flood protection in the long term while also preserving the existing structure.
- The new inspection gallery in the dam offers perfect opportunities for monitoring, reaction and intervention.

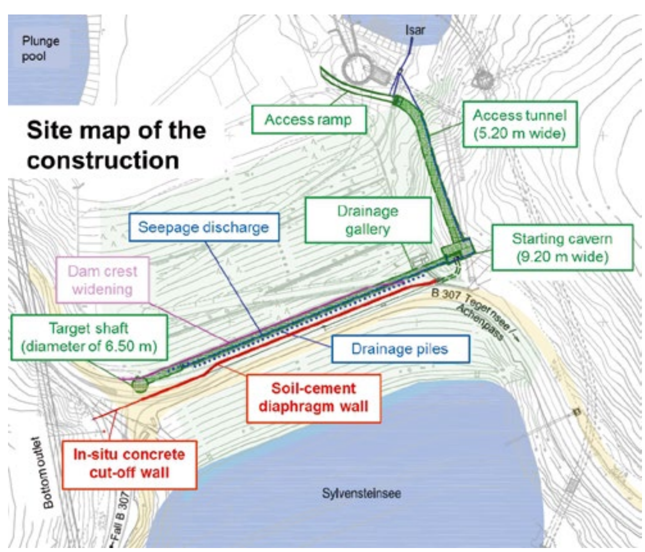

Figure 1: Sylvenstein reservoir: Site map of upgrade work on the Sylvenstein reservoir (diaphragm wall, drainage tunnel/inspection gallery, drainage piles)

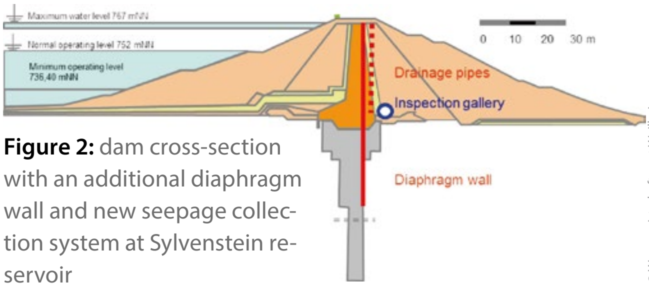

Figure 2: dam cross-section with an additional diaphragm wall and new seepage collection system at Sylvenstein reservoir

Further exploration drilling followed in 2011 and 2012. The Geotechnical Centre at the Technical University of Munich carried out these analyses as part of a research and development project in the field of geotechnics [5].

2 An overview of the upgrade plan

After more than 50 years in operation, the dam was upgraded to the state of the art with the upgrade measures described below (**Figures 1** and **2**), which entailed creating a new high-quality sealing and a seepage monitoring system allowing exact measurements to be taken. It is thus equipped to handle the larger demands that would come from major flood events in the long term. The Bavarian Water Management Agency started giving the matter preliminary consideration until 2009 [2], [4]. Plans were completed under the leadership of CDM Smith in 2011 after a Europe-wide invitation to tender was held.

The Sylvenstein reservoir is located in a valuable natural habitat. The dam itself is situated in a flora-fauna habitat area. A solution using measures in the dam's interior was pursued to avoid changing the structure's external appearance. Diaphragm wall options with varying positions vis-a-vis the dam axis and core were primarily considered to improve the core's sealing effect. A two-phase diaphragm wall with bulkheads was considered as an option for later monitoring. Potential solutions with bored pile walls were ruled out due to the lack of dimensional accuracy when creating perpendicular elements in the required depth. The grouting options did not bring about the desired extensive improvement to the core; in addition, further disturbances of the zoned dam cross-section could not be ruled out [4].

A two-phase diaphragm wall proved to be the best solution. Its position in the core was offset slightly towards the downstream face compared with the dam's axis. This solution aimed to create the work space needed to handle heavy construction machinery on the dam crest and retain some of the existing pore water pressure sensors to take measurements during construction work. The appropriate depth for the diaphragm wall was determined using several exploration drillings in the sub-soil (see above) and finite element calculations.

Figure 3: New bridge built over the plunge pool, building site equipment and pipe store at the base of the Sylvenstein dam

Construction work was carried out between 2011 and 2015. The widening of the crest needed for construction and structural reasons and the temporary bridge needed to detour the B 307 around the building site was among the preparatory work. As a result, key traffic ties between the Inn valley/the Achen Lake region and the upper Isar valley were maintained constantly during work to construct the diaphragm wall. A new bridge over one of the two plunge pools had to be created to access the building site on the toe of the downstream face of the dam (**Figure 3**).

The upgrade plan is essentially divided into three main measures.

Diaphragm wall

Installation of a diaphragm wall up to 70 m deep in the dam core. This wall goes about 25 m deep below the level of the dam foundation into the original ground of the Isar River (**Figure 4**). The diaphragm wall was created as a two-phase wall in 2012 using cutting and large gripper devices from Bauer Spezialtiefbau.

Inspection gallery

To construct the inspection gallery, an access tunnel first had to be blasted into the bedrock in the eastern flank of the rock (Sylvenstein Mountain) in 2013. The underground horizontal inspection gallery going through the dam into the opposite western flank of the Hennenköpfl Mountain was drilled from the starting cavern at the end of the access tunnel using a tunnel boring machine (TBM) (Figure 1). The TBM was retrieved using the 43 m-deep vertical target shaft, which had also been blasted in the interim. Wayss & Freytag Ingenieurbau carried out this work.

Drainage piles

In 2014, the Porr company created 54 drainage piles with a depth of about 41 m between the diaphragm wall and the inspection gallery (Figure 2) to withdraw and pinpoint the location of potential seepage. A centred drainage pipe withdraws potential leakage water, which collects in the base of the pile from where it is emptied in the new inspection gallery and measured.

Road construction and landscaping work and interior fittings for the gallery system were then carried out in 2015.

The Sylvenstein reservoir performed its main tasks of protecting against floods and elevating low water levels without any restrictions during the entire construction period.

The upgrade project was 50 % co-financed by the European Fund for Regional Development (EFRD). The EFRD is contributing towards risk preparedness and resource conservation by providing funds for upgrading the Sylvenstein reservoir.

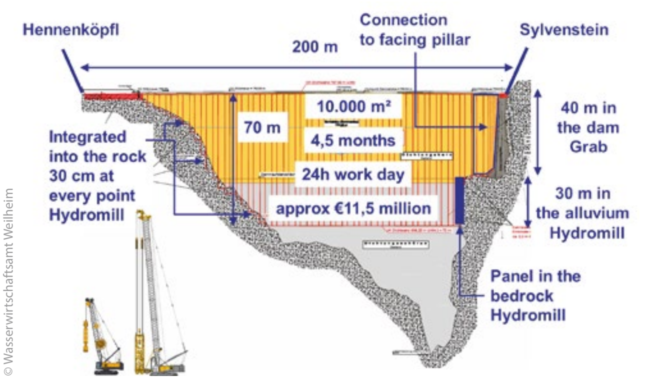

Figure 4: Diagram showing areas where the grab and hydromill were used and performance data during creation of the diaphragm wall by Bauer Spezialtiefbau GmbH

3 Construction of the diaphragm wall

The previously investigated valley alluvions consist of alternating layers of sand-rich and silt-rich gravel material, sometimes with deposits of lake marlstone layers. Highly variable permeability was found within the sub-soil, which had been grouted with a clay-cement suspension during previous construction work.

A minimum depth of 60 m was determined for the planned diaphragm wall to ensure stability against internal erosion, in other words to prevent the migration of fines. A depth of 70 m was ultimately chosen, which made it possible to connect the diaphragm wall with the extensive lake marlstone layer and could be just produced with the technical equipment available. Secure connection to the bedrock was put out to tender for the dam‘s lateral abutments, with cutting into the compact main dolomite as an option [8].

A 1 m-thick diaphragm wall of clay concrete, which was to be constructed as a two-phase wall, was chosen because of the considerable depth. A minimum tensile strength of 500 kN/m² and maximum stiffness of 450 MN/m² were required to absorb deforming forces. The required permeability stood at $k_f < 1 \cdot 10^{-9}$ m/s (laboratory value). The diaphragm wall mix was optimised in advance using a variety of test series.

A diaphragm wall grab and a hydromill were deployed at the same time, so that the short construction time planned for the 10,000 m² diaphragm wall could stay on track (Figure 4). The space required for the work and crossover traffic for large machinery was created by widening the dam crest by 4 m with a downstream angular retaining wall. This additional space has been used as another strip of parking spaces since the project‘s completion. Machinery reconfigurations (assembling the cutter along the direction of travel of the support frame (**Figure 5**) saved the need for extra work space. A mixing unit was set up at the B 307 alongside the dam crest to create and prepare the bentonite slurry.

The individual panel width of 3.2 m and the required 40 cm overlap resulted in 62 primary and secondary panels for the 170 m-long diaphragm wall. Its upper section (in the core area), up to a depth of 40 m, was taken out by the grab. The lower area to the lowest point of 70 m and bonds into the rock on both sides (at least 30 cm is required and the main dolomite has an unconfined compressive strength of 21-96 MPa) were created using the hydromill fitted with pin chisels (Figure 5). This division of work meant that material excavated by the grab did not have to be segregated by the separating plant, and the hydromill‘s higher performance could be used optimally at greater depth.

Figure 5: The Bauer Spezialtiefbau diaphragm wall grab and hydromill cutter in operation

The diaphragm wall was moved 3 m downstream of the dam axis to avoid hydromill collisions with old metallic grout pipes which had been left in the lower subsoil. As a result, most of the old dam core could remain intact. One particular challenge was that work unexpectedly encountered a row of old sheet piles left over from the time when the main trench was built and was perpendicular to the axis of the diaphragm wall. A complex photogrammetric investigation, confirmed by exploratory boreholes using georadar, indicated that sheet piles several metres long might be encountered that could hardly been removed by existing machinery. Three old pieces of the sheet piles (each about 1.40 m long) were detached and retrieved from a depth of about 45 m with the help of the hydraulic hydromill, supported by the use of chisels to pierce ground that had become compacted with grouting in the past. A continuous homogenous diaphragm wall without discontinuities could hence be created.

Perpendicular alignment of the finished diaphragm wall was reviewed by two independent measuring methods [9] and was well within the required tolerance. A minimum thickness of the diaphragm wall of 45 cm (in the joint of two neighbouring panels) should thus be complied with at a depth of 55 m and with a minimum thickness of at least 20 cm at a depth of 70 m. Actual deviations averaged just about 6 cm. The maximum of 11.5 cm was also well below the permitted limit.

To ensure high reliability of supply, concrete for the diaphragm wall was created using a building site mixer at the foot of the dam and pumped to the dam crest using a pipeline. Quality control in the form of self-monitoring conducted by the construction firm using permanent sampling of the bentonite stabilising slurry and diaphragm wall mass at the construction site (including determining yield point, filter cake compression, specific weight, pH value, consistency, strength, rigidity and permeability) was complemented by specialist construction supervision and external monitoring [6]. All samples of the diaphragm wall material met the agreed parameters.

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Figure 6: Installation of the TBM on the cradle; behind it the press station with six hydraulic cylinders for 2,500 t thrust and above it the driving control station

Changes to the dam and subsoil during the production of the diaphragm wall were tracked and observed in an intensive measuring programme using the remaining pore water pressure sensors. This made it possible to prove the achieved sealing effect at an early stage (even without the new seepage measuring system) [7].

The construction site operated around the clock five days per week. It took an average of about 24 hours to sink a diaphragm wall panel 70 m deep, with concreting work requiring about 12 hours. Therefore, an average of four panels could be created each work week. The entire construction phase took place between April and November 2012, with work on the diaphragm wall itself lasting from May to August.

Road traffic over the dam was maintained during construction work by having a single lane controlled by traffic lights open over a temporary bridge (weight restricted to 3.5 t or less) on the dam‘s upstream slope. The reservoir‘s normal operating level was lowered by about 5 m during construction to increase the resilience of the entire system. The legally enshrined basic functions of the Sylvenstein reservoir (flood protection and elevating low water levels) were maintained during the entire construction phase.

4 Creation of the inspection gallery

An access tunnel around 90 m long (5 m high, 4 m wide) with a starting cavern at its end had to be created in the main dolomite to construct the inspection gallery. Excavation by means of a gentle blasting method revealed a compact, stable bedrock so that no additional rock stabilization was needed, with the exception of a shotcrete support system.

The press station was assembled in the 16 m x 8.50 m x 7.50 m (length x width x height) starting cavern, which pushed the full-face TBM (**Figure 6**) as well as the following reinforced concrete pipes through the roughly 175 m-long excavation path within the dolomite and the fill dam. An AVND 2,500 AB Herrenknecht machine with a 400 kW cutter head drive was used to ram pipes. The cutting wheel at the head of the TBM, referred to as a mix shield (3.05 m diameter), is fitted with disc cutter and cutting knives to drive through bedrock and loose rock. The working face was supported by bentonite slurry at pressure of 0.5 bar during propulsion, which simultaneously removed loosened material as a solid/liquid mixture. To this end, the bentonite slurry was cleaned from excavated material in the separation plant and enriched with fresh material before being fed back into circulation. The transition zones between the bedrock and the dam, some of which were abrading, were stabilised with hard gel injections before being driven through by the TBM.

The individual pipe sections, which were 2.8 m long (pipe storage area shown in Figure 3), had an outer diameter of 3 m (inner diameter of 2.4 m) and weighed 18 t, were pushed in directly behind the TBM by the hydraulic press station with a maximum pressure of about 2,500 t to provide lasting stabilization of the excavated profile. The individual sections of the pipeline, which is comparable with a link chain, were sealed against the water pressure by an outer stainless-steel cuff with a rubber ring. A steel bulkhead was added at the end of the feed device (between the presses and the final reinforced concrete pipe) as an emergency sluice to shield the building site area in the event of damage (water entering the work face or fire in the tunnel).

Surface friction was reduced when driving the tunnel around 175 m-long by pressing bentonite into the narrow ring gap between the drill head‘s low overcut and the concrete tunnel pipe (**Figure 7**). Separate grouting points were envisaged in every third pipe section to this end. Two expansion units were installed in the pipeline as a precautionary measure to further reduce press forces, although they were not used. A peak advance rate of eight pipe sections in a 24-hour working period was reached, in other words 22 m per day. About 40 % of the time was used for pure advance work, 60 % for opening and closing the press unit as well as inserting a new pipe section. The target cavern was reached after 16 days of work. Deviations between the gallery and its target axis were less than 2 cm vertically and up to 4 cm laterally. They are thus considered exceptionally low. A 43 m-deep vertical target shaft (6.50 m diameter) and a horizontal target tunnel about 20 m long had to be blasted out at the end of the excavation path beforehand. This was used to retrieve the TBM, which had been dismantled into two pieces. The target

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Figure 7: Tunnelling, laser, transport and supply lines, bentonite grouting to reduce surface friction takes place using the yellow grouting line

Figure 8: Preparations to install the drainage filter (slotted pipes and sump pipe)

Figure 9: View of the inspection gallery with the seepage collection system and interior fitting

shaft has been fitted with a stair tower and now serves as an emergency exit.

For safety reasons, the gallery was driven under the protection of the new diaphragm wall. Operation of the dam was thus not limited during the entirety of the tunnel driving work, and the water level did not need to be lowered during this stage.

Flood event in June 2013

Heavy rainfall at the start of construction work on the gallery led to a major flood event in June 2013 [9]. The Sylvenstein reservoir's manageable flood control storage ultimately was almost 100 % filled on 3 June 2013. The retained volume reached approximately 61 million m³. For the first time since its creation in 1954, the old spillway started operating from 3 to 4 June. Maximum inflow into the reservoir was 675 m³/s (at 5pm on 2 June 2013). However, just 60 m³/s was released at that time.

Since the situation was especially critical in the section of the Isar River in Lower Bavaria and following sections of the Danube River, an attempt was made to optimise management of storage capacities in favour of these river sections in constant dialogue between the Bavarian Ministry for Environment and Consumer Protection and the State Office for Water Management Weilheim. The dam's new diaphragm wall allowed the highest-ever impoundment level to be reached and maintained without concerns for a long period of time to relieve the strain on downstream areas. Consequently, flow in Munich had been almost halved from 1,300 m³/s (without reservoir action) to 770 m³/s. Unlike other water bodies, the Isar River did not suffer any significant damage. Blasting work at the two tunnel construction sites was suspended as a precautionary measure during the flood event [10].

5 Drainage piles

To withdraw potential seepage, 41 m-deep drainage piles were built between the diaphragm wall and the inspection gallery starting in May 2014 [8]. The 54 large piles, which were drilled with diameters of 900 mm, and with an axis-centre distance between them of 2.8 m, were created as piped piles with an auger drill. Some 2,150 m of the entire drilling path went through the dam's core and the old filter, while 92 m of the bore pile length penetrated the bedrock in the flanks. In this case too, perpendicular alignment is well below permissible tolerances. Just like with a well for water extraction, a slotted pipe in these piles withdraws seepage water, which collects in a plastic (HDPE) sump at the base and is discharged into the new inspection gallery. Altogether, about 1,700 m of filter pipe, 110 m of filter pipe with a stainless-steel wire wrap filter (**Figure 8**) and 400 m of solid wall pipes (diameter 200 mm) were installed. The filter pipes are surrounded by 2-5 mm of filter gravel. About 1,250 m³ of filter gravel was used. Horizontal boreholes (diameter 178 mm) were drilled into the plastic sumps from the inspection gallery and equipped with solid wall pipes (diameter 100 mm) in order to connect the sumps with the inspection gallery.

Altogether, work on the large vertical drill holes and small horizontal drill holes lasted about five months. Four drainage piles were created each workweek on average. Road traffic travelled over the dam crest during construction using a single lane controlled by traffic lights, as needed.

The interior fitting of the inspection gallery with measuring technology took place in the winter of 2014/2015 (**Figure 9**). The measuring technology allows for constant, section-by-section monitoring of seepage amounts throughout the entire dam. Therefore, the stipulations of DIN 19,700 Part 11 – Dams for direct, section-by-section measuring of seepage amounts are met. Each individual drainage pile can also be irrigated individually using a system of shafts and hoses and thus checked for functionality. A pressure bulkhead is installed at the end of the inspection gallery to be of the safe side, designed to handle 40 m water pressure.

Construction work ended in 2015 with the restoration of the dam crest and the two main roads (**Figure 10**) and renaturation of the building site areas. There is now a strip of parking spaces and a footpath along the B 307 on both sides on the dam crest.

6 Summary

The dam and subsoil of the Sylvenstein reservoir were equipped with a new, high-quality sealing and a seepage measuring system permitting measurements section by section after more than 50 years in operation [3]. This was the first time in Germany that a 70 m-deep diaphragm wall, which also cut into the rock foundation on either side of the wall, was created while the dam continued operating. The new dam sealing is monitored using drainage piles and a walkable inspection gallery, which was driven from the Sylvenstein Mountain's compact bedrock through the entire dam body into the opposite abutment on the Hennenköpfl Mountain side – without hindering dam operations. This was a unique constructional feat that was achieved for the first time worldwide. In future, the Sylvenstein reservoir will be able to properly and safely handle the high demands of future large flood events. This was already proven in impressive manner during the June 2013 flood event.

Beyond measuring seepage, drill holes might go from the inspection gallery into the deeper subsoil, if needed. Measuring devices might also be installed to observe flow and pressure in the subsoil. This will open up many courses of action in relation to the inspection gallery for future measurements and grouting work. This work might be carried out quickly and precisely due to optimum elevation [11].

With the construction work described here, the State of Bavaria is able to accomplish high-quality modern flood protection on the Isar River, which has impacts beyond the Munich metropolitan area into Lower Bavaria. Modifications to bring the dam, which was more than 50 years old, to the latest technical standards and the specifications of DIN 19,700 incurred manageable costs of EUR 23 million and was thus well below the forecast sum of EUR 25 million [12]. All timing and cost specifications were therefore met.

The Sylvenstein reservoir's two main tasks – flood protection and raising low water levels – were met without restrictions during the entire construction period.

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Ertüchtigung des Dichtungs- und Kontrollsystems des Sylvensteinspeichers

Die Talsperre Sylvensteinspeicher wurde in den Jahren 2011 bis 2015, nach über 50-jähriger Betriebszeit, mit einer zusätzlichen Dichtwand in Damm und Untergrund sowie mit einem neuen Sickerwasser-Messsystem an den Stand der Technik angepasst. Diese Ertüchtigungsmaßnahmen stellen auch eine Vorsorge gegen die Folgen möglicher Klimaveränderungen dar, da die zeitlich enge Abfolge und Größe der letzten Hochwasserereignisse eine künftig stärkere Beanspruchung der Talsperre erwarten lassen. Die Baumaßnahmen mit Kosten von rund 23 Mio. Euro wurden aus dem Europäischen Fonds für Regionale Entwicklung kofinanziert.

Figure 10: The new B 307 over the widened dam crest in autumn 2015

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