Retrofitting Sylvenstein dam with a cut-off wall and control gallery

T. Lang and G. Overhoff, Bavarian Water Management Agency, Germany

The Sylvenstein dam was upgraded after 50 years in operation, with the provision of a diaphragm wall (a two-phase cut-off wall) at the existing dam and subsoil, as well as a new measurement system consisting of drainage piles for seepage and a control gallery. These additional upgrades are considered as preventative measures to provide for the possible consequences of climate change, as the magnitude and frequency of recent flood events imply that larger impacts on the dam could be expected in the future.

The 48 m-high, 180 m-long embankment dam at the Sylvenstein reservoir in Germany is located on a 100 m-deep valley cut, which the Isar river carved into the dolomite at the site, and subsequently filled with sediment. The gulch was sealed during construction in the 1950s with a seven-row grout curtain. The thin, central impervious earth core wall consists of artificially composed clay concrete (gravel, fine sand and silt with a 1 per cent sodium bentonite addition) and connecting upstream and downstream moraine gravel filters. The supporting mass of river gravel, along with the pitched slope and the vegetation on the face of the embankment, shape the image of the dam's surface. Since its commissioning in 1959, the reservoir has helped flood mitigation and protects the Isar runoff in the dry seasons by supplying water. At the same time, clean renewable electricity is generated for the public grid. In addition, Sylvenstein has become an attraction for local people and tourists. From 1994 to 2001, the oldest state-owned reservoir in Bavaria was modernized, with the construction of a second spillway, with a capacity of 400 m^3/s; the dam was also heightened by 3 m, thus increasing the flood-control storage capacity by 20×10^6 m^3 [Lang, 2012[1]].

Settlement of the dam structure over the deep and narrow glacial gulch caused the formation of fissures in the dam core, which were grouted with injection campaigns in 1970 and 1987/88. Detailed investigation of the dam core, with the porewater pressure sensors found inside, and the interpretation of the measurements, indicated possible changes to the sealing system [LfW and LfU, 2002, 2003 and 2007[2]]. Furthermore, the seepage flow measurement system had been damaged by the earlier settling of the dam and the grouting work, so that it was not possible to identify the sources of leakage, which also indicated the need for a new measurement system.

1. The rehabilitation concept

The improvement measures which were implemented (see Figs. 1 and 2), comprising a new efficient sealing system and an accurate seepage monitoring system, have restored the dam to state-of-the-art condition after 50 years of operation. It is now equipped to handle the possible effects of climate change and the demands on it that would result from a major flood event.

The preliminary deliberations of the Bavarian Water Resources Management Administration [Overhoff and Raab, 2008[3]; Overhoff *et al*., 2010[4]] were underway until 2009, and 2011 saw the conclusion of the planning process. The construction measures began in 2011 and were completed in 2015.

The improvement measures primarily fall into three main categories:

- installation of a cut-off up to 70 m deep, in the core wall and the upper part of the foundation (in 2012);
- construction of a control gallery (in 2013), including an access tunnel, a starting cavern and a target shaft; and,
- installation of 54 drainage piles with a depth of approximately 41 m, between the cut-off wall and the control gallery (in 2014).

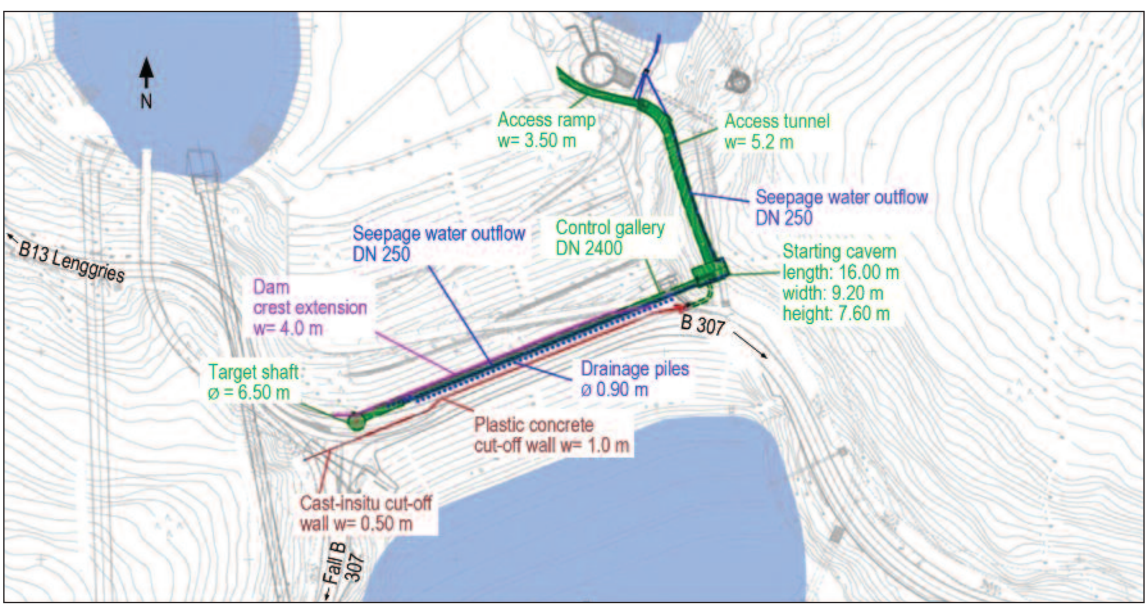

Fig. 1. Site map of retrofitting measures (cut-off wall, control gallery and drainage piles).

Throughout the construction phase, the Sylvenstein reservoir had to maintain its main tasks of flood protection and low water elevation.

2. Construction of the cut-off wall

The pending valley alluviums were investigated intensively in advance through a number of boreholes extending to a depth of 140 m. They are composed of an alternating sequence of sand and a poor clay gravel mixture, sometimes with deposits of lake marlstone layers. Strongly fluctuating permeability was found within the subsoil, which had been grouted in the past with a clay-cement suspension.

A minimum depth of 60 m was determined for the planned cut-off, to ensure stability against internal erosion. A depth of 70 m was chosen, which made the integration of the large lake marlstone layer possible, and was achievable with the technical equipment available.

A 1 m-wide cut-off wall of clay concrete was chosen because of the considerable depth, which was to be constructed as a two-phase wall. A diaphragm wall cutter and grab were deployed at the same time, so that the short construction time planned for the 10 000 m^2 cut-off wall could stay on track. The necessary space required for the work had to be created by widening the dam crest by 4 m, and this was done by providing a downstream angular retaining wall.

The individual panel width of 3.2 m and the required overlap of 40 cm resulted in 62 primary and secondary panels for the 170 m-long cut-off. The upper cut-off section of the core area (about 35 m deep) was taken out by the grabber and the lower area, to the lowest point of 70 m, along with the bonds of at least 30 cm into the cliffs on both sides, were done with the slurry cutter, see photos (a) and (b).

The cut-off was moved 3 m downstream of the dam axis to avoid cutter collisions with old metal grout pipes which had been left in the lower subsoil. As a result, most of the old core insulation could remain intact.

The changes to the dam and the subsoil during the creation of the cut-off were observed by an intense measurement programme with the help of the remaining porewater pressure system. This made it possible to verify, within a short time, the seal effect which had been achieved, without the new seepage water measurement system [Bauer, Lang, Overhoff and Strobl, 2013[5]].

(a) View of the cut-off construction with the grabs and hydrocutters on the crest of the Sylvenstein dam in the summer of 2012; downstream, widening of the dam crest with an angular retaining wall. The reservoir water level is lowered by about 5 m. This is a view from the webcam of the State Office for Water Management [Wasserwirtschaftsamt Weilheim, 2015[8]].

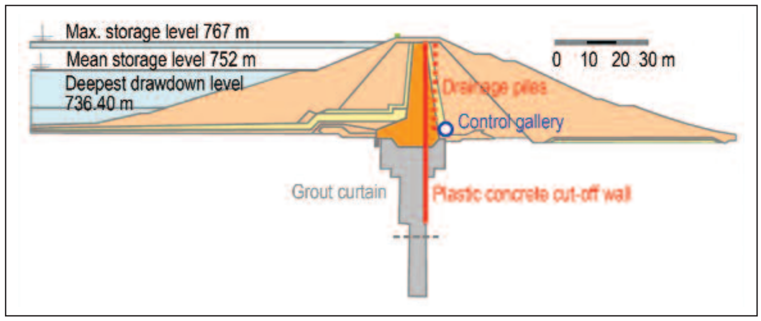

Fig. 2. Dam cross section, showing the additional cut-off wall and seepage water measurement system.

(b) The Bauer slurry claw and cutter.

The normal water level of the lake was lowered by about 5 m during construction, to increase the resilience of the whole system, see photo (a). The basic functions of the Sylvenstein reservoir (flood protection and increasing the water level during dry periods) could be maintained throughout the whole construction phase.

3. Construction of the control gallery

To construct the control gallery, an 80 m-long access tunnel with a starting cavern at the end had to be built at the foot of the rock at Sylvenstein dam into the main dolomite [Lang and Overhoff, 2015[6]]. Driving in to the

(c) Installation of the TBM. Behind it: the thrust unit station with six hydraulic cylinders for 2500 t thrust, and above that, the driving control station.

(d) The tunnelling, laser, transport lines and supply lines.

rock, avoiding explosive technology, revealed a compact, stable mountain range, so that no additional rock protection was needed, with the exception of a spray concrete support system.

The thrust unit was built in the approximately 16 × 8.50 × 7.5 m ($L \times W \times H$) starting cavern, which pushed the full section 3.05 m-diameter tunnel boring machine (TBM), see photo (c), as well as the following reinforced concrete pipes through the roughly 190 m-long excavation path of dolomite and fill dam.

The 18 t individual pipe sections (which were 2.8 m long, with an outer diameter of 3 m and an inner diameter of 2.4 m) were pushed in directly behind the TBM by the hydraulic thrust unit, see photo (d). The individual sections of the pipeline, which are comparable with a link chain, were sealed against the water pressure by an outer stainless steel cuff with a rubber ring, before being inserted.

A target tunnel, about 20 m long, and a 41 m-deep vertical target shaft with a diameter of 6.5 m, had to be blasted out at the end of the pipe-jacking section in advance, so that the TBM could be taken apart (divided into two pieces) and lifted out. The target shaft now serves as an emergency exit.

The target cavern was reached after 16 days, see photo (e). Protection was provided during this work by the new cut-off wall. Thus the operation of the reservoir did not need to be limited during the tunnel driving works, and the water level did not need to be lowered at this stage.

(e) Drill head of the TBM in the target cavern after it had drilled approximately 190 m through the tunnel.

At the beginning of the construction period for the control gallery, heavy rainfall caused the major 2013 flood event in Germany. Thanks to the flood retention capacity of the Sylvenstein reservoir, the peak discharge of the Isar into Munich could be reduced from 1300 m^3/s (which would have been the flow volume without Sylvenstein dam) to 770 m^3/s. No significant damage was observed along the Isar river, in contrast with other rivers in the same region. Because of the new cut-off wall, it was possible to reduce outflow from the dam over a long time period, which was necessary as the levees along the Danube were overloaded and even breached in two areas.

On 3 August 2013, the manageable flood control capacity of the Sylvenstein reservoir reached 99.7 per cent of its impoundment volume. The storage volume reached 61×10^6 m^3, and almost all of this volume was required. The maximum inflow into the reservoir was 675 m^3/s (on 2 June 2013 at 17.00 hrs) while at the same time the maximum permissible outflow was only 60 m^3/s. With careful reservoir management and limited release of water, it was possible to maintain the load on the downstream abstractors in the region towards Munich-Freising-Landshut, and the Danube towards Passau, to a minimum.

4. Construction of the drainage piles

To keep the seepage water to a minimum, starting in May 2014, 41 m-deep drainage piles were built behind the cut-off wall about 1.2 m from the seepage tunnel [Langhagen, Weiss and Lang, 2014[7]]. The 54 large piles, which were drilled with diameters of 900 mm, and with a distance between their central axes of 2.8 m, see Photo (f), were created as piped piles with a drilling rig. The slotted pipes in these piles provide for the collection of the drainage water, which then flows into the base of the seepage tunnel.

Instrumentation installed inside the seepage tunnel provides permanent, sectional surveillance of the seepage water along the entire length of the dam.

5. Lessons learnt

The dam and foundation at the Sylvenstein reservoir were equipped with a new efficient cut-off wall and a system for precise measurement of seepage water, after more than 50 years of operation. This was the first time in Germany that a 70 m-deep plastic concrete cut-off wall, which also cut into the foundation rock on either side of the wall, was installed while the dam remained in operation. Monitoring the new sealing system is possible with the drainage piles and from a control gallery, which was drilled in compact rock through the whole dam and into the opposite abutment, all without hindering the normal operation of the dam. This represents a major accomplishment of construction. The Sylvenstein reservoir will be able to handle reliably high demands in the future, when it can be assumed that larger floods will occur. This has already been confirmed during the flood event of June 2013.

In addition to the control function, additional drillings could be made into the lower subsoil from the control gallery, see photo (g), should it be necessary. It is also possible to install measurement points, to monitor pressure and flow in the foundation. This will provide opportunities for many courses of action in rela-

(f) Construction of the drainage piles.

tion to the control gallery, for more measurements and grouting work. These can, in turn, be executed quickly and precisely because of the optimum elevation [Bauer *et al*., 2013[5]].

The State of Bavaria is assured of a high standard of modern flood protection on the Isar river and in the Munich metropolitan area, extending to Lower Bavaria, thanks to the construction measures which have been described here. The adaptation of the more than 50 year old dam to the current state of the art and to DIN-Standards, was achieved within a manageable budget of €23 million. The European Regional Development Fund (ERFE) provided 50 per cent of the finance [Lang and Overhoff, 2016[9]]. ◊

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(g) View of the control gallery, the seepage control system and the interior fitting.

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T. Lang

G. Overhoff

Dr Tobias Lang began his training in 1986 with a construction company and civil engineering studies at TU Munich, Germany. In 1994 he became Scientific Assistant at TU Munich and Chair of the Hydraulic Laboratory of Hydraulic and Water Resources, Oskar von Miller-Institute Obernach where he completed his Doctorate research. In 1999, Tobias began the management of a EU flood defence project for the Hessian Water Agency. He joined the Bavarian Water Management Agency in 2001 where he has held a number of positions until 2008 when he became Head of the Department of Dams, Hydrology, Flood Forecasting and Warning at the State Office for Water Management Weilheim as well as specialist officer of the Sylvenstein and Windach reservoirs. In 2015 he joined the Bavarian Ministry for Environment and Consumer Protection in the Department of Dams, River Stages, Polder and Storage Management.

State Office for Water Management Weilheim, Pütrichstraße 15, 82362 Weilheim, Germany.

Gregor Overhoff studied Civil Engineering at TU Aachen between 1973 and 1979. He then joined Dyckerhoff & Widmann (a construction and construction management company). After completing a traineeship with the Bavarian Water Management Administration, he undertook various positions in the sector, including at the dam construction office in Nürnberg (to help with the construction of Roth Lake dam). He later worked with the Bavarian State Agency for Water Resources. He has also held positions with the State Ministry of Land Development and Environmental Surveys, the Bavarian State Agency for Water Resources (Head of Department for Water Engineering, Machinery and Electrical Engineering), and the Bavarian State Agency for the Environment (Head of the Hydraulic Engineering, Plants on Waters Department). In 2009 he joined the Ministry of Environment and Consumer Protection as Head of the Department of Dams, River Stages, Polder and Storage Management.

Bavarian Ministry for Environment and Consumer Protection, Rosenkavalierplatz 2, 81925 München, Germany.