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Repairing the Aubecken pumped-storage reservoir with an impermeable core using a Mixed-in-Place method

The existing sealing system at the Aubecken pumped-storage compensating reservoir at the River Rhine has shown signs of leakage since its commissioning in 1978. A rehabilitation project in the form of adding a new sealing within the existing body of the dam was selected to safeguard durability. The Mixed-in-Place method was used to do so. Demanding geotechnical subsoil conditions and the required connection to the bedrock were especially challenging. The project's success was proven using test filling.

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1 Description

The Aubecken pumped-storage reservoir was created between 1975 and 1978 on the High Rhine's Auinsel (Au Island), which lies downstream of the Dogern weir. It is bordered by the head race for the Albbruck-Dogern Rhine hydropower station to the north and by the Rhine river bed to the south (**Figure 1**). With a capacity of 2.2 million m³, the reservoir serves as a compensating reservoir for pumped-storage hydropower plants run by Schluchseewerk AG. The reservoir is managed using a combined intake and outlet structure. Up to 140 m³/s of water from the Rhine River can be transferred from the head race into the reservoir. Maximum discharge into the Rhine River stands at 100 m³/s.

An average layer of about 7 metres of material was removed from the original site to create the reservoir. On the Rhine side, an earth-fill dam was created along the original shore line. On the head race side, an aggradation on the Aubecken reservoir side was added to the existing canal dam. This area is also referred to as a separating dam.

This ring dam has a combined sealing system. The slope's upper section is sealed using asphaltic concrete facing. The sealing system's lower section is a vertical diaphragm wall that is embedded into the bedrock. These two elements are connected by a reinforced head beam. The base of the reservoir did not need to be sealed since the ring dam is completely sealed into the bedrock. A circumferential drainage pipe (DN 300 or DN 400) is located behind the head beam to discharge seepage, for monitoring the sealing and to prevent uplift at the asphaltic concrete facing.

2 Reason for the rehabilitation project

Since operation began, seepage measurements taken within the circumferential drainage system have revealed considerable shortcomings on the part of the sealing system. Partial rehabilitation projects in the 1980s and 1990s involving the diaphragm wall joints and underground grouting did not yield lasting success.

Exceptionally high seepage occurred when the reservoir level was high, especially during the winter. In turn, this sometimes even led to pressurised conduit flow in the drainage pipes. In addition, groundwater levels observed in the vicinity of the reservoir varied considerably by several metres, depending on reservoir management. Sand deposits were also found during regular inspections of the circumferential drainage system's seepage shafts. Regular precise surveys of the encircling dam revealed advancing settlement behaviour, especially in the separating dam. The conclusion that was drawn was that distinct flow conditions in the subsoil or in the body of the dam was causing material to shift.

Extensive measuring campaigns and expert opinions indicated that seepage was occurring, especially in the diaphragm wall joints and in the area where the diaphragm wall met the bedrock. Safeguarding the durability of the separating dam in the long term without restricting operations was therefore no longer guaranteed. The decision was made to undertake an extensive rehabilitation of the reservoir's sealing system near the separating dam so as to minimise the risk of an unscheduled stoppage and limitations on reservoir management.

A feasibility study found that adding a new impermeable core stretching from the dam crest into the bedrock was a target

Synopsis

- The Mixed-in-Place method was successfully used, even though the subsoil was found to be non-homogeneous and variable containing silt to large rocks.
- This method offered considerable time and cost savings compared with alternative construction techniques.
- The body of the dam can be drained using the existing drainage system without perforating the facing.

Figure 1: Aerial view of the Aubecken

variant. Compared with the alternatives, this comparatively sophisticated solution minimised the required restrictions in reservoir operation before and during rehabilitation, had lower future maintenance costs and, in particular, was expected to have the best-quality sealing function.

Before further implementation planning was undertaken, seven bore-holes were drilled into the bedrock along the separation dam towards the head race. These holes were upgraded to groundwater measuring points. On the one hand, these points allowed the dam's structure to be verified. On the other, groundwater measuring points helped to provide quality assurance during and after construction work and should also be used to monitor the separation dam in the long term.

3 Planned measures

3.1 Overall strategy and constraints

Broadly in keeping with the feasibility study, the tender documents provided for rehabilitation of the entire separation dam between the transition to the encircling dam in the west and the intake/outlet structure in the east of the reservoir using a sheet pile cut-off about 980 metres long going between 12 and 20 metres deep. This cut-off wall was to be located as close as possible to the dam shoulder on the Aubecken reservoir side due to the large number of power and other cables in the dam crest area. **Figure 2** shows a site plan for this project, while **Figure 3** depicts a standard cross-section.

The project team decided not to remove the asphaltic concrete facing on the upstream face and to add new slope reinforcement with riprap for cost reasons. This makes sure that the body of the dam does not become saturated up to the original diaphragm wall and that asphaltic concrete facing remains water-tight in the event of high water levels. To minimise pressure behind the asphalt concrete facing to a reasonable level, especially when water levels fall rapidly, the adits to the existing drainage pipes, located about every 100 metres, are to be opened to discharge water from the body of the dam through drainage layers and drainage pipes without causing any damage. A test area was to be created to check the effectiveness of this approach. The test

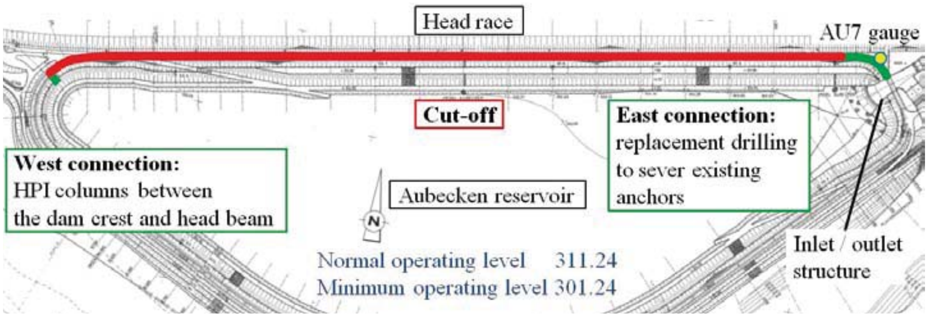

Figure 2: Site plan for the Aubecken rehabilitation project

can monitor pressure conditions behind the asphalt concrete facing using 11 pressure sensors installed at varying heights. The functioning of two core drillings filled with single-grain concrete should also be checked as an additional drainage option.

Moreover, the upper section of the planned sheet pile cut-off should have a load-bearing capacity. Consequently, any potential bank slides in the old facing, which will not require further rehabilitation over the coming decades, should not have an impact on the dam's stability.

In addition to performing drilling, seven heavy ram probes were sunk in advance of work to complete the geotechnical survey. However, just two of these probes reached the bedrock level and thus the expected final depth. Subsoil areas were addressed as follows with the help of all available geotechnical documents (Figure 3):

- Embankment: Coarse gravel with rocky formations.
- Recent fluvial deposits: Sandy to silty
- Rhine gravel: Coarse gravel, some of it block-like
- Bedrock: Tonstein with a weathering horizon of a few decimetres

During the construction project, a layer of riprap was encountered in the transition area between the old head race dam and the later aggradation resulting in the separation dam. This area had not been detected during geotechnical surveys.

A chemical analysis of drilling samples showed soil heavily contaminated by coal and turf deposits in one drill-hole.

An intensive study of old survey plans and photos from past construction periods proved beneficial. This work revealed anchors that will cross the marked-out route for the cut-off at a length of about 50 metres on the connection to the east. At the time of construction, these anchors served to anchor the retaining structure for an excavation pit in the area of the intake/outlet structure.

To the west, the impermeable core near the crest and existing diaphragm wall beneath the head beam were to be connected with the shortest connection downhill along a 1:1.75 slope. This work was essentially grouped into three main sections from west to east:

- West: Connect the new cut-off to the existing diaphragm wall with a head beam.
- Cut-off with connection to the very dense bedrock.
- East: Sever anchors installed when the reservoir was constructed and create a connection to the intake/outlet structure.

3.2 Sheet pile cut-off

In the light of the geotechnical situation with rocky and blocky fractions, it was clear that sealing with sheet piles was not directly possible here. Consequently, a decision was made to opt for drilling holes with a diameter of 880 mm, which were to be filled with a sand-gravel material with a grain size of 0.06/8 mm.

These replacement borings aimed to remove gravel interspersed with stones and to learn more about the depth of the

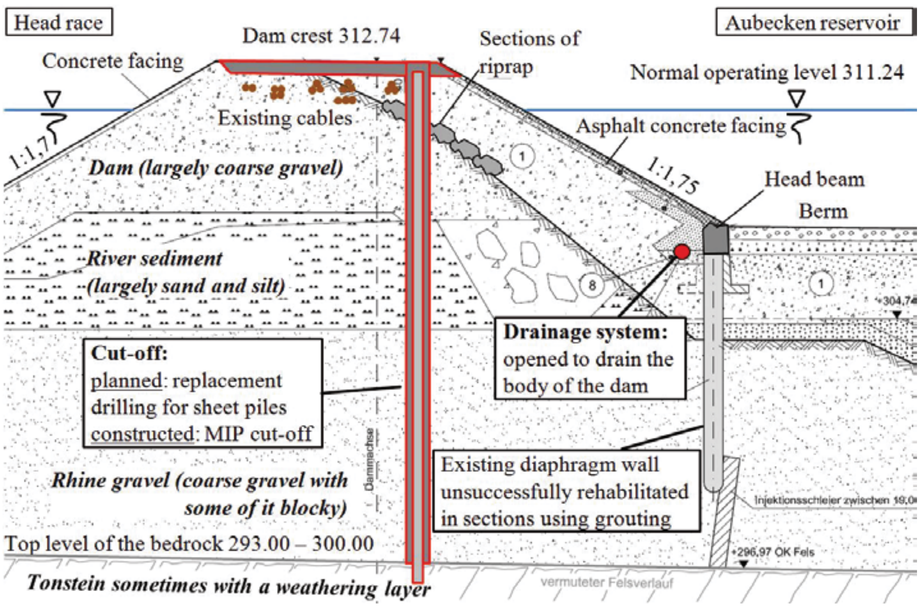

Figure 3: Standard cross-section of the Aubecken rehabilitation project

bedrock and weathering horizons. In addition, this work sought to gather information about how long the sheet pile cut-off needed to be and, of course, how to install sheet piles without any problems. Where possible, the project also attempted not to remove the entire weathering horizon to guarantee a better connection to the very dense bedrock. The team decided against welding lances on to the sheet piles to retroactively seal the connection to the bedrock using grouting and against installing clay or similar material in areas adjacent to the bedrock. The amount of soil material to be replaced was put at approximately 13,500 m³.

3.3 Western connection

To the west, a jet grouting wall going through the Aubecken reservoir's asphaltic concrete facing was to guarantee a tight connection between the sheet pile cut-off near the dam crest and the existing diaphragm wall with a head beam at a 10-metre length along the slope's fall line. This wall must be at least 1 metre thick. Experts had previously ruled out other forms of grouting.

3.4 Eastern connection

The plan was to sever strand anchors in the eastern connecting range of the cut-off using the drilling rig's bit and replace spoil similar to boreholes along the separation dam. Located in the ground since the reservoir was created, these anchors no longer serve a function today.

The connection to the intake/outlet structure itself was to take place through two jet grout columns, one on the upstream face and one on the downstream face.

3.5 Award of construction services

Several separate proposals and variants of the planned measures put out to tender were presented during the evaluation of bids. After a great deal of discussion and input from experts, the team opted for the bid submitted by Bauer Spezialtiefbau GmbH using the Mixed-in-Place (MIP) method rather than the sheet pile solution described above. The following services were bid, awarded and performed:

- Cut-off: MIP cut-off without pre-drilling connected to the bedrock by drilling through the weathering layer.
- Western connection: A temporary banking on the slope supported by a steel structure and addition of a three-row curtain using jet grouting method starting at the banking.
- Eastern connection: Severing anchors and pre-drilling using a drilling rig. Removal of steel parts and coarse stones and refilling of the holes. Creation of the cut-off using a MIP machine. Connection to the intake/outlet structure using two jet grouting columns.

4 Mixed-in-Place method

Patented by Bauer, the Mixed-in-Place process has been successfully used in flood protection projects, but also in retaining structures for excavation pits and foundation work for more than 25 years. The main feature of this method is in-situ mixing of soil with a suspension of cement and bentonite. In-situ soil is

Figure 4: Manufacturing of the Mixed-in-Place cut-off using a RTG RG 25 rig with a triple augur

broken up using a triple auger before working in the binder suspension. The triple auger drills down to the final depth as the suspension is added. During the subsequent homogenisation process, each augur's rotational direction is varied in such a way that a vertical material cycle is created in the MIP cut. **Figure 4** shows the MIP device in operation at the Aubecken dam.

The MIP cut-offs are made using a double pilgrim step process in order to make sure that the wall is continuous and seamless. This patented process also features additional processing of the overlap areas comprising primary and secondary cuts. This ensures that the triple auger penetrates and mixes each wall element at least twice (**Figure 5**).

Benefits of the MIP method include:

- The use of a triple auger with continuous flights homogenises heterogenous layered soil structures and turns them into a uniform soil concrete of consistent quality.
- The use of in-situ soil as a building material/aggregate conserves resources and eliminates the need for complex transportation of spoil and concrete to make sheet piles. A significant reduction in CO_2 emissions also materialised compared with the sheet pile solution because raw material production is much less energy intensive.
- From a holistic life-cycle analysis perspective, MIP technology is highly attractive compared with conventional special engineering methods.
- Low-vibration wall manufacturing using rotary drilling reduces the strain on dams that have already suffered damage. Noise emissions are also minimised.
- The MIP method is highly productive so construction time is short. For instance, in this project, the construction period was about half of what had originally been planned with replacement drilling and the installation of a sheet pile cut-off.

Altogether, Bauer made 13,500 m^2 of MIP cut-off with a width of 550 mm and a length of 980 metres. Drilling depth ranged from 12.5 metres at the intake structure in the east to 20.4 metres on the western end point of the separation dam requiring rehabilitation. MIP work was performed between the start of October and the start of December 2016 in day and night shifts. The team used a RG 25 vibratory rig from RTG Rammtechnik with a triple augur and a Bauer BG 24 H rotary drilling rig, which performed replacement borings in some areas. Gaps to the existing seal were also closed using high-pressure injection (HPI).

5 Challenges during construction

With a crest just 8.15 metres wide, the working surface on the separating dam was severely limited and no reserve space was available. For instance, when the MIP device was set up and ready to operate, there was not enough space to drive by another piece of construction machinery. Another complicating factor was that the building site – practically a cul-de-sac – could only be accessed from one side.

The difficult, extremely heterogenous quality of the subsoil also posed a challenge. Artificial dam fill with riprap stones, some of which had to be removed with replacement borings, and embedding into the bedrock, which was in part covered by banks of conglomerate material, created particular challenges for the technology and tools used and significantly extended limits on the use of the MIP method. Discrepancies relating to very large stones were immediately detected using the augurs' patented online verticality measurements and additional cuts could be prescribed.

In one area, boulders below the surface tipped the drilling augurs so much that one broke, could not be retrieved and had to be left underground. The critical area could not be bypassed using other MIP cuts since 110 kV lines were located in close proximity to the drilling axis. Consequently, this gap was closed using HPI columns.

Special occupational safety measures also had to be taken. Since the head race has a strong current, it was mandatory for site workers to wear lifejackets. A safety barrier was also installed in the work area. The RG 25 vibratory rig was also retrofitted with a walkway to ensure worker safety during drilling work on the narrow crest. Since work also took place at night, it goes without saying that glare-free lighting of the entire building site was provided.

Once the entire project was completed as planned in February 2017, unforeseeable leaks ultimately occurred in an area

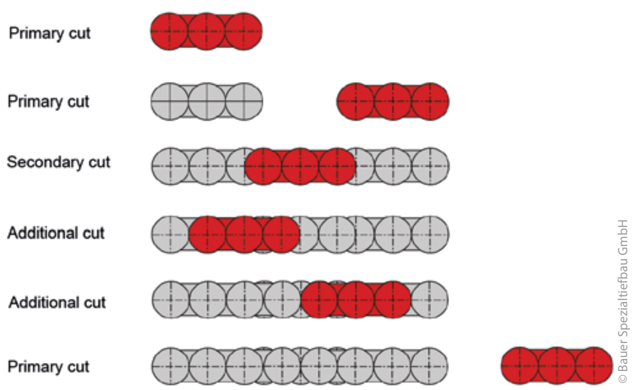

Figure 5: Sequence of the double pilgering method in the MIP process

right at the intake structure, which was outside the area rehabilitated by Bauer. Water from the Aubecken reservoir apparently entered the 1.5-metre-wide gap between the intake/outlet structure on the north side wall and the old retaining structure for the excavation pit that had been filled with coarse material. From there, water reached anchor holes behind the MIP cut-off, which were not permanently sealed at that time. This gap was later successfully sealed using high-pressure injection.

6 Test filling

Once rehabilitation work was finished, test filling was performed to assess the quality of the new sealing level in the area of separating dam and to observe the impact of uplift on the old asphalt concrete facing near the separating dam. In a first phase, the reservoir was filled from the minimum operating level to the normal operating level and the reservoir water level was kept constant for 18 hours so that the body of the dam could become saturated. In a second phase, the reservoir was then emptied at maximum water discharge to simulate a load scenario of quickest possible lowering of the water table.

During the emptying process, pressure at 11 piezometers located in the test area was analysed simultaneously to reduce the discharge in time if necessary in the event of critical pressure. These readings showed that pressure beneath the asphalt concrete facing decreased at the same rate as water level fell in the reservoir and was clearly below the previously calculated limit value. Therefore, practical proof was provided that draining the body of the dam using existing drainage systems in the dam toe worked very well and there was no need for additional relief holes to be drilled in the slope area.

Groundwater measuring points installed at a distance of 100 metres apart along the separation dam serve to evaluate the functioning of the MIP cut-off. The reaction of groundwater levels depending on reservoir management was analysed before and after test filling. An evaluation of readings showed that fluctuations in the groundwater level were cut by an average of 84 % as a result of the project. In particular, maximum groundwater levels in the separation dam were lowered by an average of two metres. Therefore, high flow gradients no longer occur in the separating dam. In the past, these had led to internal erosion within the body of the dam.

Figure 6 highlights the effectiveness of this work. The diagram shows the water level at groundwater measuring point Au7 depending on the level of the Aubecken reservoir as an example. This measuring point is located close to the intake/outlet structure (Figure 2). The cluster of red points depicts conditions before the rehabilitation work. The groundwater level rises four metres higher if the reservoir is filled. The cluster of blue points shows conditions after the MIP cut-off has been created. This work did improve matters, but significant groundwater changes based on reservoir management practices are still apparent. The cluster of green points shows conditions after four more HPI columns were created in the area connecting to the intake structure. These points are almost in a single line. This means that reservoir management no longer has a noticeable impact on the groundwater level, which in turn is evidence of the very good effectiveness of the sealing work.

7 Conclusion

When opting for the separate proposal to create an MIP cut-off, it was clear that this method would push the limits in several areas. Nonetheless, this technology had an edge by virtue of the quality assurance work, such as the existing gauges and permanent display of each MIP cut that can later be evaluated in graphic form, as well as the ability to connect the cut-off through the weathered rock into the dense rock using the MIP process