

Updating Ennepe

V Bettzieche and J Kienle explain how costs for rehabilitation work at the Ennepe dam in Germany were reduced substantially by the construction of an inspection and drainage gallery instead of placing a large concrete lining on the upstream face of the dam

SOUTH of the Ruhr district in Germany, the Ennepe dam was built in 1904 and increased in height by 10m in 1912. Erected from quarry rocks as a gravity retaining wall, it has a total span of 320m and a height of 51m.

During an inspection in the 1980s, it became clear that the dam did not correspond to the current status of technology. The dam was designed without taking the pore pressure and respectively the uplift into account, based on the basic design principles applied on the early masonry dams. Therefore the entire structure proved to be rather slender. As a result, the Reservoir Supervision Authority demanded the immediate adaption of the dam to the established technical standards.

Before any rehabilitation work was carried out, different concepts were developed to help decide on the most effective way to adapt the dam. As with many other older masonry dams, the first idea was to build a concrete diaphragm wall at the upstream side of the Ennepe dam. First calculations showed that this would cost about US\$37.8M.

When the Ruhr-River-Association took over the operation of the dam in 1997, a different concept was developed with the intention of stabilising the entire structure by reducing uplift.

The most important elements of this concept were:

- The construction of a drainage gallery close to the upstream face at normal reservoir level.
- Drain masonry and bedrock with fans of drainage borings.

The costs of this work was calculated at about US\$18.9M, including:

- Replacement of the intake gates and conduits
- Rehabilitation of the gate towers.

FINITE ELEMENT METHOD

Before rehabilitation work was carried out, a feasibility study was performed using three detailed finite element method (FEM) models including:

- A seepage model for analysing the effect of the internal water forces.
- A temperature flow model quantifying the influence of the seasonal temperatures and the resulting internal stresses.



Above: Illustration showing the rehabilitation concept . Right: View of the 51m high Ennepe dam, which was built in 1904

- A crack propagation model proving the stability and the occurrence of cracks, essentially affected by the stresses determined by the first two models.

Different scenarios were simulated such as normal conditions with average water levels, temperatures and rain fall, but also extreme floods and winter conditions with low temperatures.

After submitting the results of the study, the Reservoir Supervision Authority agreed upon the entire rehabilitation concept, provided that continuous monitoring would prove the success of the rehabilitation.

DRAINAGE GALLERY

It was decided to use a tunnel boring machine (TBM) for the construction of the drainage gallery. Even though there was no specific experience with the use of a TBM under these conditions, there seemed to be big advantages concerning the quality of the tunnel. The lack of structural disturbance of the bedrock and the masonry surrounding the tunnel opening would make any kind of lining unnecessary, turning the gallery into a large scale drainage boring.

The length of the gallery (370m), as well as the steep gradients (30°) and small radius of the curve (150m), demanded the use of a small and manoeuvrable tunnel boring machine. A Robbins 81-113-2 TBM was chosen for the work.

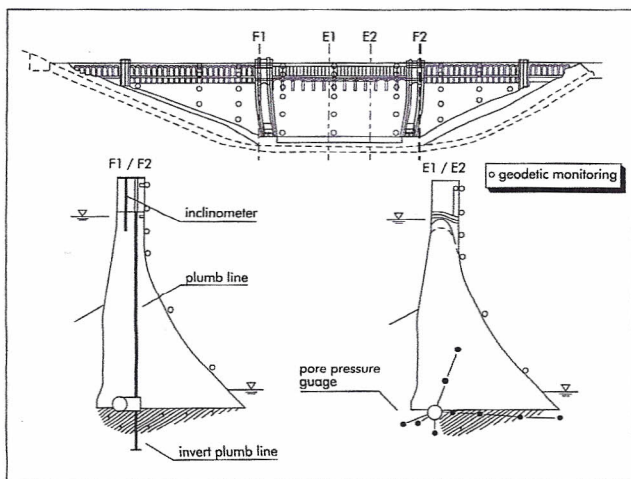
In less than a year the TBM produced a smooth circular gallery, which could remain mostly unlined with no additional support. After completion of the drainage gallery, boreholes could be easily drilled from the gallery in different directions. In total 1350m was drilled. All boreholes are cored to ensure high quality.

MONITORING SYSTEM PERFORMANCE

One of the prerequisites for the rehabilitation works was the monitoring of the system performance. Therefore, the instrumentation concept included the installation of pendulum systems, both hanging and inverted, pore water pressure piezometers, temperature sensors, inclinometers and pore-water and seepage measurement stations.

The hanging and inverted pendulum systems serve for the control of lateral movement of the dam. For this purpose, two boreholes had to be drilled through the entire wall of the crest, throughout the control tunnel, down to a depth of 20m into solid rock foundations.

Pendulum wires are installed in these boreholes and tensioned by means of plumb lines (hanging system, from crest to tunnel) or by a floating unit in a tank (inverted pendulum, from tunnel into solid rock). Niches were blasted in the control path to house monitoring instruments. The movements of the pendulum wire and the retaining wall are controlled by laser distance transducers and recorded by an automatic data acquisition system to which all the other installed instruments are connected.



Above: monitoring layout, profiles F1 and F2 are pendulum systems, E1 and E2 cover pore water pressure gauges and temperature sensors

In several measuring profiles, additional boreholes were drilled, both horizontally and vertically towards the crest. Two profiles were equipped with vibrating wire pressure sensors, and two other profiles equipped with temperature sensors PT100.

The installation of the measuring instruments into those boreholes caused substantial difficulties. For this reason, special packer anchors developed by Boart Longyear Interfels were used, which, after being injected with grout, provided a sealant of the borehole with regard to boundary circulation. In some boreholes, a water pressure of up to 3 bar was also recorded. The gallery serving as open drainage collects the seepage water which is pumped outside.

Three automatic seepage water measuring stations in total are installed in the gallery. The water gathered is led to a small overflow weir with a calibrated V-notch. The height of the water level in front of this weir is measured by means of ultrasonic sensors and transmitted to the central data recording unit, which converts and displays the measured flow rate.

One part of the data recording unit is installed in the tunnel and housed in waterproof control cabinets made from high grade stainless steel. The complete unit is protected against water pressures up to 10m water column. An additional data recording unit is installed on top of the wall crest, which records the water temperatures in the reservoir and the temperatures of the air at the inside of the wall.

All data acquisition units are linked through fibre optic cable leading to a processing station located outside the dam. The entire system is continually accessible via a modem.

TAKING MEASUREMENTS

Using the data of the pore pressure gauges and the seepage water measuring stations, a good estimation can be made about the water in and outflow through the gallery.

A comparison of these measurements with the values expected on the basis of the seepage model is possible by averaging the measured outflow of the drillings. The quantities measured at the drainage in the masonry dam were below the predictions of the model, while the quantity of the rock drainage was similar.

The measured values illustrated the tightness of the masonry dam, which was substantially higher than assumed. The measurements of pore pressure were also analysed constantly and verified the success of the rehabilitation.

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