100 Years of Experience in Ageing of Masonry Dams and life-time-based Rehabilitation

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ABSTRACT: Since more than 100 years the Ruhrverband (Ruhr River Association) is responsible for water quality and water resources management in the catchment area of the Ruhr River in the State of Northrhine-Westphalia, Germany. For this important duty, the association owns and operates 8 reservoirs with a storage capacity of about 470 million m³. Some of these dams were build as masonry dams at the beginning of the 20th century. During their time in operation many ageing-based problems appeared, as the dams had been constructed based on the fiction that the reservoirs could be emptied for maintenance about every 10 years. But the need for reservoir water was so high, that none of the reservoirs could be emptied in the following 50 years. Some repair work had to be done, which (in same cases) unfortunately was not successful as the dams were not constructed lifetime oriented.. In the last years new concepts of rehabilitation had been developed, to guarantee a life-time based rehabilitation. At the example of the masonry dams of the Ruhrverband these concepts are explained: ageing of masonry dams and rehabilitation by driving control-galleries into the dam, ageing of the bedrock and rehabilitation with injections and life-time oriented concepts for the reconstruction of the bottom outlets.

1 INTRODUCTION

At 1904 the first reservoirs were retained in the catchment area of the river Ruhr. (Two of them, the Ennepe dam and the Fürwigge dam, are owned by the Ruhrverband). The constructor of these dams, Prof. Intze from the University of Aachen believed, that it should be possible to empty these reservoirs after some time of operation to maintain the dam and the operating equipment. In the following time, up to the II. World War, many other dams (masonry dams and embankment dams) were build, without taking account to the maintenance and rehabilitation of these dams.

In the 1950th it was obvious, that a lot of repair work had to be done at the reservoirs, which were in operation up to 50 years without any appreciable rehabilitation. Many of the works, that had been done in those years, were started precipitately and caused more trouble than positive results, i.e. the drainage systems of the masonry dams were unintentionally but completely filled by injection material (which was fully counterproductive).

Since about 1980 the Ruhrverband improves his dams, taking later rehabilitations into account. Lifetime oriented concepts of rehabilitation had to be developed, based on the basic necessity that the reservoirs could not be emptied during the repair works. Three domains had to be considered with their specific problems: the dam itself (specially the 100 year old masonry dams), the bedrock and the outlets.

2 AGEING OF MASONRY DAMS

During the first 20 years of the last century about 30 gravity dams were built in Germany. These structures were designed as so-called “Intze-type” masonry dams with build-in drainage systems but without taking the pore pressure, respectively the uplift into account.

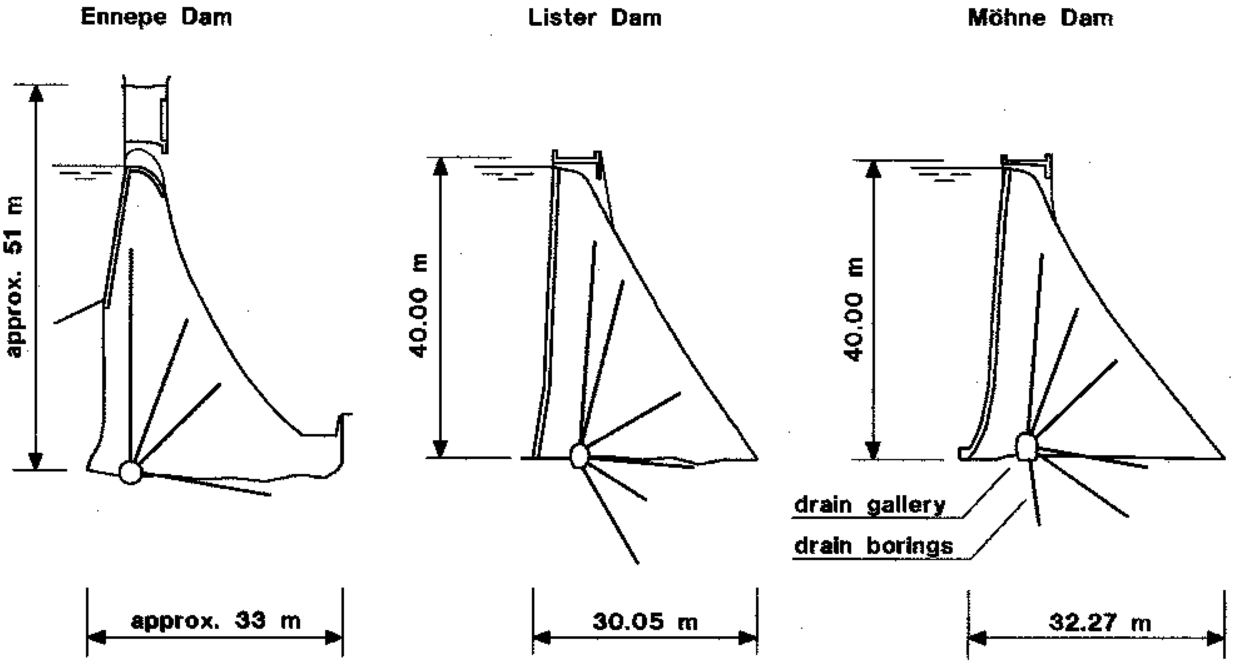

Figure 1. Masonry dams of the Ruhr-River-Association, rehabilitated with drain systems

Several circumstances caused the malfunction of these systems after more than 60 to 90 years in operation. The Moehne Dam (40 m high, build in 1913) was damaged in World War II and rapidly rebuild without the drainage system. The Lister Dam (42 m high, build in 1912) was reconstructed because it was included in the new Bigge Reservoir in 1965. The Ennepe Dam (50 m high, build in 1904) had to be rehabilitated because the drainage system was unintentionally filled by injections in the sixties (Fig. 1).

As this rehabilitation concept turned out to be rather cost-efficient the Ruhr-River-Association implemented drainage galleries and drain borings inside of these three masonry dams. These galleries serve as means for the inspection of the condition of the foundation surface, as well as drainage system for increased water pressures. Their special advantage is the fact, that they can be used later on for cost-efficient repair works of the dam and the bedrock.

2.1 INVESTIGATION OF THE EFFECTS FROM DRAINAGE SYSTEMS

In June 1997 the 93-year-old Ennepe Dam was taken over by the Ruhrverband. The Ennepe Dam had to be adapted to the established technical standards and safety regulations. The construction of a drainage- and inspection gallery (Fig. 2) with a Tunnel Boring Machine has been the most spectacular part of the rehabilitation work:

The realisation of the concept ”draining the masonry dam” was allowed by the Reservoir Supervision Authority firstly because numerical models had proved the feasibility and secondly under the reservation, that measurements had to prove the success of the rehabilitation.

The most important elements of this concept were (Heitefuss, C. & Rissler, P. 1999):

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

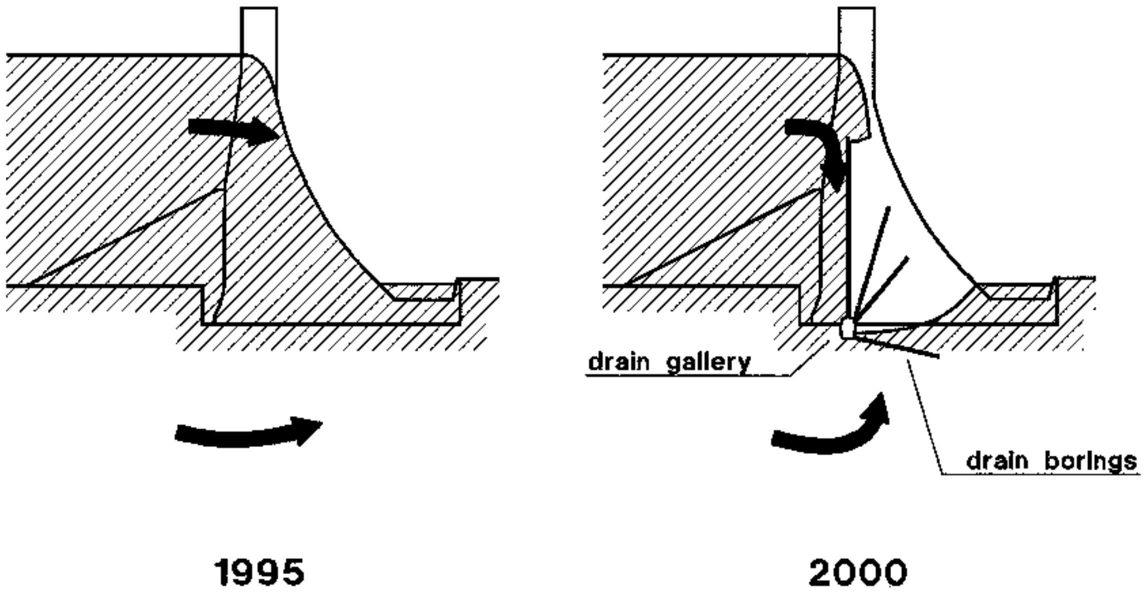

Figure 2. Realised concept of rehabilitation, using draining at the Ennepe Dam

2.2 A-PRIORI STUDIES OF THE DRAINAGE SYSTEM AND CALCULATION OF THE STABILITY OF THE DAM

For the optimisation of the arrangement of the drainage borings a flow model was provided. This mathematical model computes the potential and pressure distributions in a section of the masonry dam and the bedrock by use of the Finite-Element-Method (FEM).

The drainage effect of this fan was examined with a lateral distance of 3 m and 4 m. The computed field of porepressure is shown in fig. 3. The seepage flow seeps from the upstream face of the dam to the drain gallery and borings. A small portions drips backward from the stilling basin into the masonry.

A free surface appears below the crest. Nevertheless the quantities of seepage through the masonry is very small, because of the small potential gradient.

A strong potential dismantling takes place between the upstream face and the first drainage. Because of the highly accepted permeability (to be on the safe side) of the intze wedge, the largest quantity of water seeps by this way and then through the upper rock layer to the drainages. Between the third drainage and the downstream face an insatiated zone develops. Due to the higher permeability of the upper rock layer, this insatiated zone reaches nearly to the inspection gallery.

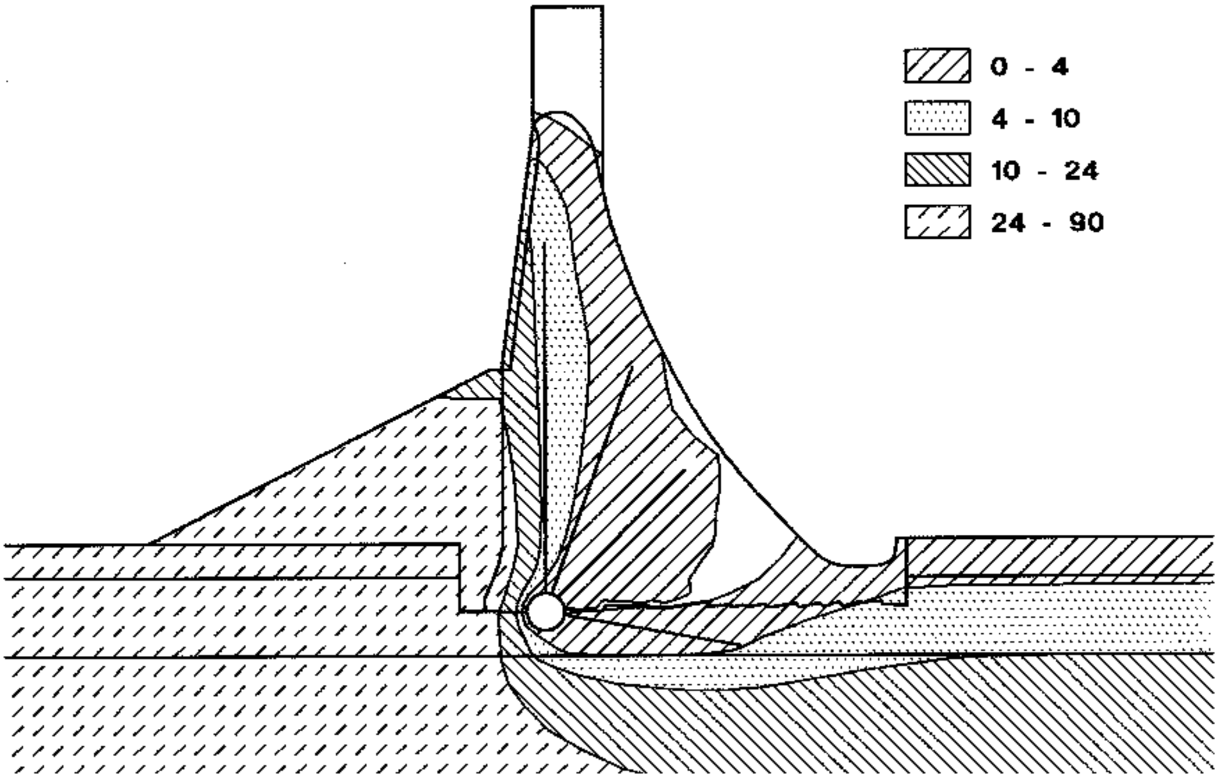

Figure 3. Seepage in a cross section of the Ennepe Dam (water pressure in m)

The rehabilitation concept was based upon a a-priori calculation of the effects from the drainage system upon the dam stability. Three numerical models, based on the Finite-Element-Method (FEM) were used:

- a fluid-FEM-model to analyse the seepage inside the dam and the effect of the internal waterforces (see above)
- a FEM-model of temperature flow for the quantification of the influence of the seasonal temperatures and from the resulting internal stresses in the dam
- a FEM-model of crack propagation to prove the stability and the occurrence of cracks, essentially affected by the stresses, determined by the first two models

A representative profile of the gravity dam, including the soil material of the so called "Intze - wedge", was approximated with a discrete FEM-model. The permeability and the mechanical properties of the materials (masonry, soil, rock) were assigned on the basis of geological investigations. Already the following measuring of the seepage-model showed, that the upper rock horizon was more permeable than the masonry. With the help of the calibrated model the seepage-situation for different sea-levels of the reservoir including different flood scenarios could be calculated.

2.3 DRIVING THE GALLERY BY AN TUNNEL BORING MACHINE

The Ruhr River Association suggested the construction of the drainage gallery with a tunnel boring machine (TBM). 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.

In the beginning there seemed to be some problems associated with the use of a tunnel boring machine,

- the curved axis of the gallery with a radius of 150 m,
- the very steep curve of the gallery at the abutments (30° angle),
- the length of the gallery of only 370 m, being unfavourable for the economical use of a TBM

The TBM started on the 24. October 1997 and reached the left end of the gallery on May 14, 1998. Seven weeks later, on August 18, 1998 the TBM appeared at the target shaft at the right abutment. The average rate of advance had been 6.7 m per day, the peak performance was 20 m per day.

It can be stated that the TBM has driven a mostly smooth and circular gallery 90 - 95 % of the gallery can remain unlined with no additional support. In the bottom reach, the upper half of the gallery runs through the masonry of the dam. Since this part is virtually ?unlined, the visitor has a remarkable view into the interior of the masonry, which is almost 100 years old.

2.4 A-POSTERIORI PROOFING

It has been mentioned, that the authorities agreed with the concept on condition that the success of the rehabilitation would be proofed by specific measurements. As one of these, the amount of seepage water was measured, which seeped from each individual drainage drilling.

A comparison of these measurements with the values expected on the basis the seepage-model is possible by averaging the measured outflow of the drillings (s. table 1). The quantities measured at the drainage in the masonry dam are clearly below the predictions of the model, while the quantity of the rock drainage reaches these. Also the values of the surface of the gallery are in the same order.

Table 1. Results of the provisional measurement of the 19 drainages in the centre of the dam, referred to a drainage fan, thus to 4 m length long the gallery

seepage	seepage model	measurement
	l/min	average of drilling l/min
out of the reservoir	11,3	?
out of the stilling basin	0,3	?
downstream face	0,2	?
vertical drains (1)	2,9	0,30
70° drains (2)	0,5	0,01
45° drains (3)	0,1	0,001
ground drains (4)	0,7	0,04
surface of the gallery	7,2	3,85

The comparison of the results of measurement with the assumptions of the a priori studies the success of the rehabilitation of the Ennepe dam and serves as basis for dam monitoring in the next years of operation.

3 AGEING OF THE BEDROCK AND REHABILITATION

3.1 AT THE BEGINNING

In earlier times attention was not so much directed to the bedrock. While constructing a dam, only shallow investigations were carried out and improvements were restricted to the surface of foundation. Moreover the underground was not suggested to be permeable to a greater extend, so seepage and uplift pressure was not considered in stability analyses.

Later on - mainly in the course of development of core boring techniques – a closer look even at deeper situated rock layers was possible and from that geologists and engineers learned to judge the bedrock in a more critical way. The most important conclusion was that not only the dams but also their bedrock were afflicted with alteration problems due to long term percolation of the fissured rock under dammed water condition.. This led – perhaps in combination with steadily changing loadings – to the development of new cracks, opening of discontinuities, decomposition and disintegration of weaker rock zones and to erosion or dissolution processes. So ageing became a severe problem only after a short period of operation resulting in water loss, uplift pressure and decreasing stability (Deutsch, R.R. 1995 u. 2003).

As a result of the described alterations, the underground of all ancient dams had to be improved by sealing with water-cement suspensions. This technique is based on injecting the rock mass under certain pressure with the aid of deep reaching boreholes with narrow spacing. In addition, a drainage system was established helping to reduce uplift pressure behind the so called grout curtain. The rehabilitations were carried out about 40 to 60 years after erecting the dams.

3.2 NEW CONCEPTS

Now knowing the effects of alteration, recently build dams were provided already in the beginning phase with grout curtains and even deep reaching concrete walls replacing weak parts of the underground together with drainage systems. Though grouting in those times started in a rough manner (the more-the better), it developed very quick to a suitable instrument to heal the rock in an economic and safe way.

In addition to the improvement works, measurement equipments were installed in boreholes or in galleries in order to control seepage conditions. Changes could now be detected in an early stage, a soon reaction was possible.

Looking at the results of nowadays underground investigations and measurements we clearly see, that in contrary to the first period of life of the older dams without protection of the underground, the ageing process now runs very slowly. For instance, rock cores with grout material show no or just a few signs of solution or alteration. We therefore can proceed on the assumption that initial improvement of the bedrock in combination with an effective control system will be a long term success in respect of functionality (sealing, stability) and life-span. It seems that in this way underground conditions are optimally adopted to the life cycle of the dams embedded in the rock. But if there is any need for further repairing in the meantime, it can be done without restrictions by using the above mentioned inspection galleries.

4 LIFE-TIME ORIENTED CONCEPTS FOR THE RECONSTRUCTION OF THE BOTTOM OUTLETS

During the last 10 years three major underwater rehabilitation projects for large hydraulic structures have been carried out by the Ruhr River Association. It has been possible to perfect not only the diving equipment but also the manufacturing and installation procedures in order to guarantee safe and economical conditions. Thus the underwater rehabilitation work has become an important alternative to conventional rehabilitation techniques for large hydraulic structures.

The layout of many hydraulic structures built during the beginning of the 20th century did not make provisions for emergency gates, since the complete draw down of the reservoirs for repair purposes was considered possible when the dams were designed. It is now known that a complete draw down of a large reservoir has to be considered as impossible, due to possible restrictions of the water supply and severe ecological repercussions as well.

If a certain reservoir level is maintained during the rehabilitation works a nearly unrestricted water supply is possible. This requires underwater work at the intake structures and the use of emergency gates for safe working conditions under atmospheric pressure inside the penstocks and the bottom outlet galleries. Thus, an important part of all projects has been the construction of support structures for emergency gates.

The placing of emergency gates is a prerequisite for the subsequent installation of guard valves and – if necessary - improved water supply facilities inside the bottom outlet galleries.

The major reason for the installation of guard valves (butterfly valves) inside the penstock galleries is the elimination of safety deficiencies in case of a pipe rupture between the upstream face of the dam and the regulating valves.

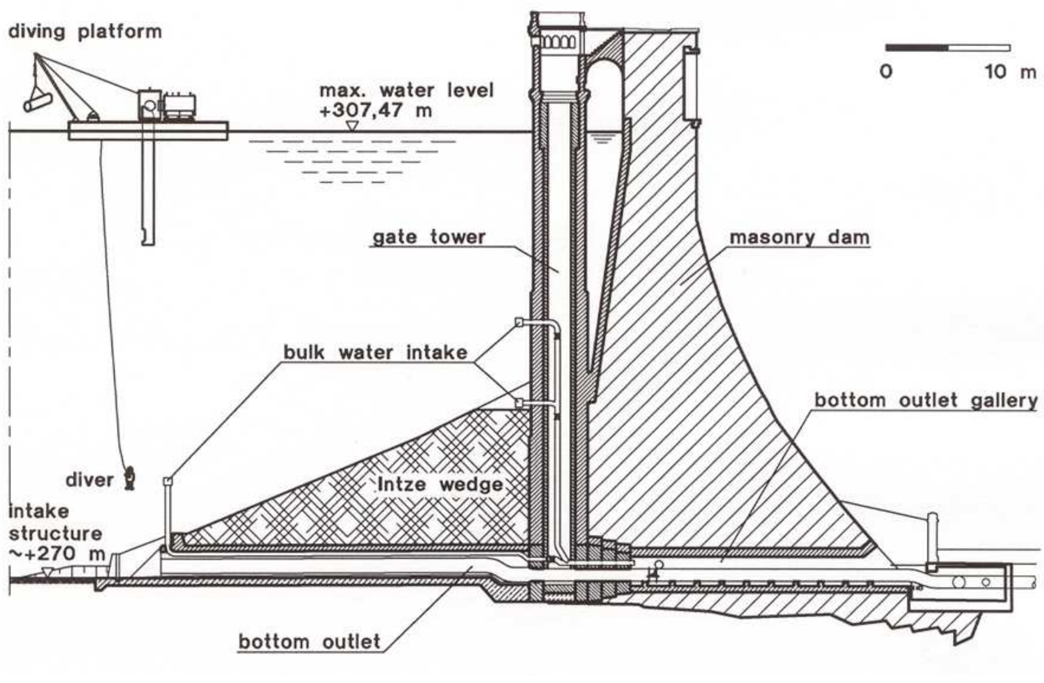

Figure 4. Cross section of Ennepe Dam after rehabilitation

Figure 4 shows a cross section of Ennepe Dam after rehabilitation with new pipework and a new guard valve inside the bottom outlet gallery. Inspection, maintenance or even replacement of this valve is now possible without restrictions anytime.

Usually the owner of a dam of the early design periods has to face the following problems:

The valves at the bottom of the gate towers have been installed in the beginning of the 20th century and show strong symptoms of deterioration and signs of spongiosis after almost one century of operation. The gate towers itself usually prove to be in very bad condition as well. Due to leakages any inspection or maintenance work at the bottom of the towers is usually impossible.

The basic principle for the rehabilitation of the entire bottom outlet structures is based upon the following ideas and has been applied at the Verse Dam as shown in fig.5:

- to move the new intake trumpets to the upstream side outside the structure
- to use the new intake trumpets as support structures for emergency gates
- to replace the old intake gates and replace them by a new guard valve inside the penstock gallery

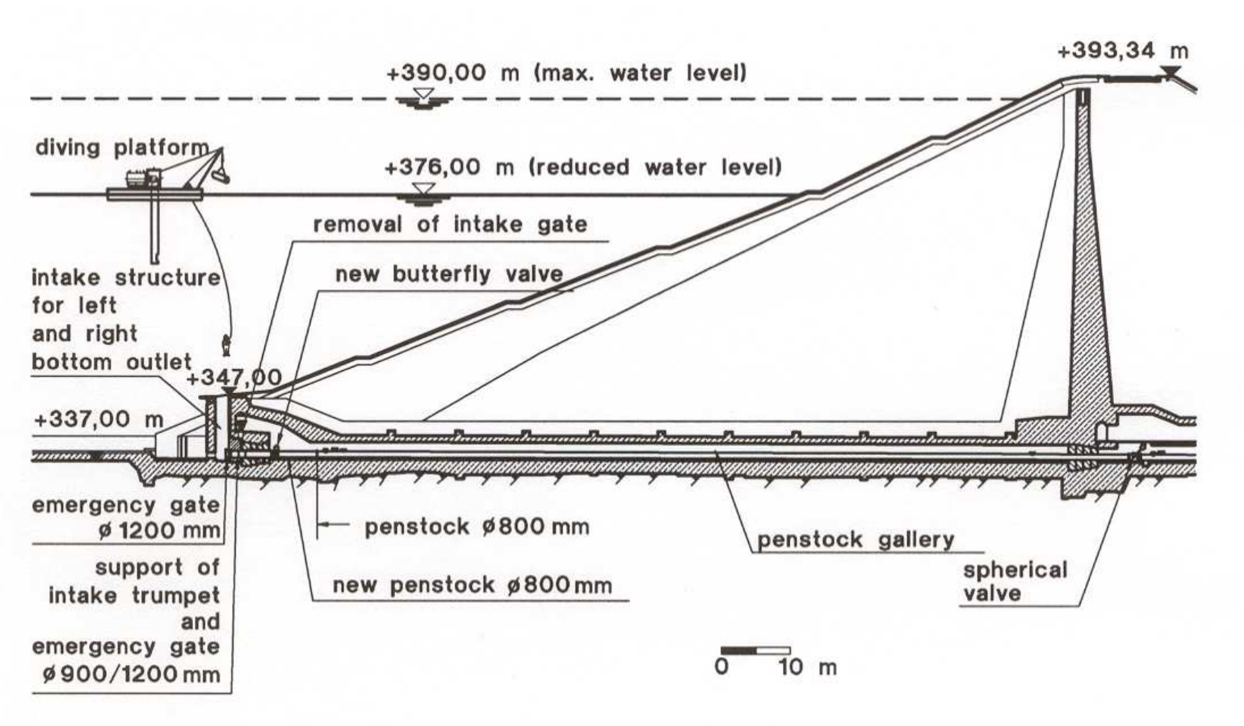

Fig. 5: Cross section of Verse Dam during rehabilitation

The lifetime of a valve or pipe is usually substantially shorter than the lifetime of the hydraulic structure itself. Therefore it has to be one goal of the new layout of the entire hydraulic structure, to allow the replacement of short/medium-lifetime components like valves without major technical and financial efforts.

Obviously this layout principle should be applied for the design of new hydraulic structures as well.

5 CONCLUSIONS

Since about 1980 the Ruhrverband improves his dams, taking later rehabilitations into account.

With these lifetime based methods of rehabilitation it is guaranteed, that future repair works can be done without emptying the reservoirs and with a minimum of impairment for the water supply of about 5 Mio. people.

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