Monitoring as a basis of cost-effective rehabilitation of an old masonry dam

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ABSTRACT: The Ennepe Dam was built from 1902 - 1904 as a a curved masonry dam with a height of 51 m and a length of 350 m. During the last years the Ennepe Dam has gone through extensive rehabilitation works. The cost for rehabilitation were reduced substantially by the construction of an inspection- and drainage gallery instead of placing a massive concrete lining on the upstream face of the dam. The rehabilitation concept was based upon a detailed feasibility study, applying different numerical simulation methods. On the basis of these simulations the Reservoir Supervision Authority agreed in the concept of rehabilitation. Major component of the official permission was the required proof of the performance of the structure by several measurements. The comparison of the real measurings with the assumptions from the “a priori”-simulations prove the successful rehabilitation and is a valuable tool for reservoir monitoring in the next years of operation.

1 INTRODUCTION

In June 1997 the 96-year-old Ennepe Dam was taken over by the Ruhrverband (Ruhr River Association), who is responsible for water quality and water resources management in the catchment area of the Ruhr River in the State of Northrhine-Westphalia, Germany since 1913. This association owns and operates 8 reservoirs with a storage capacity of about 470 million m³. The Ennepe Dam has to be adapted to the established technical standards and safety regulations. The construction of a drainage- and inspection gallery (Fig. 1) with a Tunnel Boring Machine has been the most spectacular part of the rehabilitation work so far and has been successfully finished in August 1998.

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.

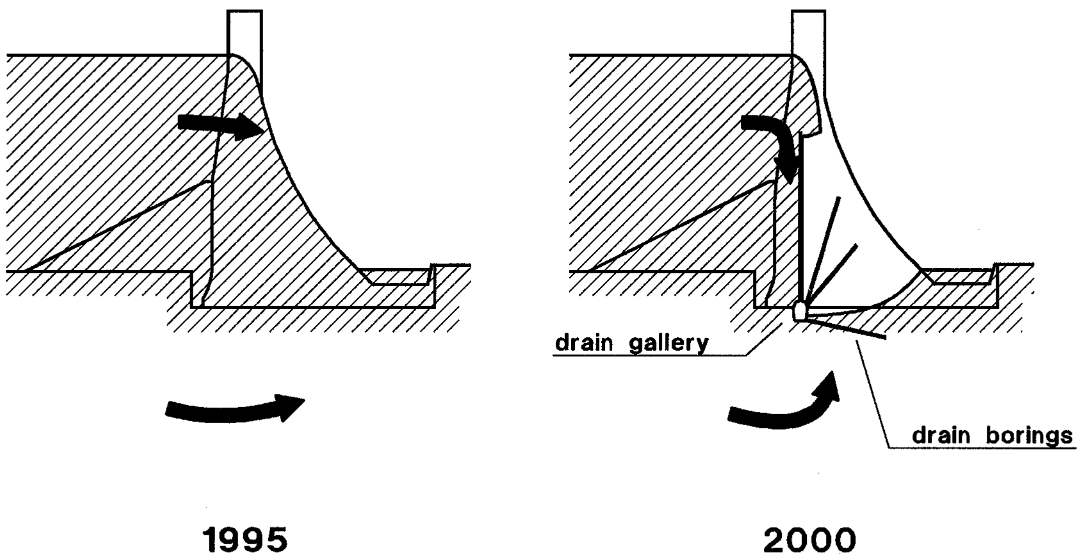

Figure 1. Realised concept of rehabilitation, using draining

2 DEVELOPMENT OF A REHABILITATION CONCEPT

As usual at many old masonry dams, a drainage system consisting of vertical stoneware pipes had been installed right behind the upstream face of the Ennepe dam. Unintentionally these drainage pipes had been filled with grouting material during repair works in 1959. Thus during the last decades there was no effective drainage system available both in the dam and in the bedrock.

The Ennepe Dam was designed without taking the pore pressure respectively the uplift into account, based on the basic design principles Prof. Intze applied at the early masonry dams. Therefore the entire structure proved to be rather slender. At the beginning of the 1980´s this problem was detected by the Reservoir Supervision Authority. According to the current view of the physical effects of the uplift phenomenon the authorities demanded the immediate adaption of the Ennepe Dam to the established technical standards.

In the following years different concepts were worked out, to adapt the dam to the established technical standards. As at many other old masonry dams in the neighbourhood the first idea was to build a concrete diaphragm wall at the upstream side of the Ennepe dam (Fig. 2). First calculations showed that this would take about 40 Mio. EUR.

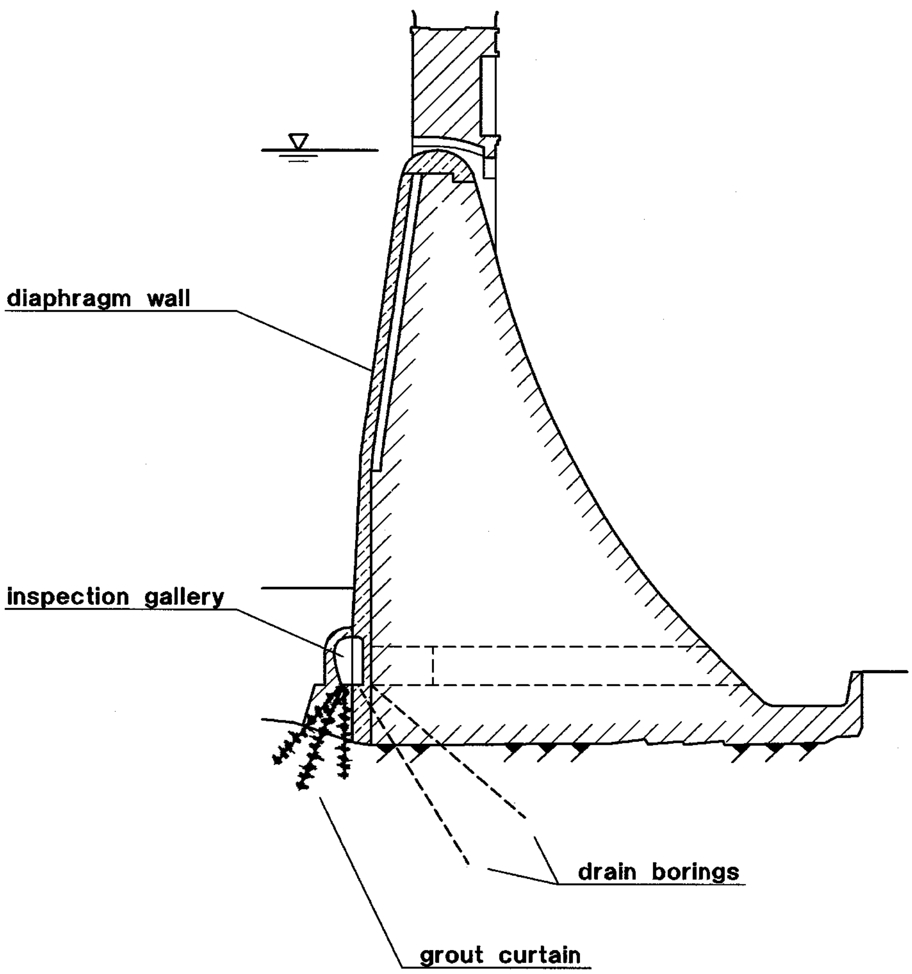

Figure 2. Earlier expensive concept, using a concrete diaphragm wall

In June 1997 the Ruhr River Association took over the Ennepe Dam from the previous owner, the Ennepe Water Association with the intention, to stabilise the entire structure by reducing the uplift.

The most important elements of this concept were:

? 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.

The costs of this Concept were calculated at about 20 Mio. EUR including

? the replacement of the intake gates and conduits
? the rehabilitation of the gate towers
? a new layout for the water supply intakes.
? This concept was developed so far, that there was no doubt about the feasibility and then submitted to the district authorities for permission and funding.

The Reservoir Supervision Authority agreed upon the entire rehabilitation concept, under the reservation, that measurements had to prove the success of the rehabilitation (Heitefuss, C. & Rissler, P. 1999).

3 A PRIORI STUDIES

The rehabilitation concept was based upon a detailed feasibility study, applying different numerical simulation methods. On the basis of these simulations the Reservoir Supervision Authority agreed in the concept of rehabilitation in 1998.

Three numerical models, using 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

? a FEM-model of temperatureflow for the quantification of the influence of the seasonal temperatures and from this resulting the 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

3.1 *FEM-Model of seepage*

A representative profile of the gravity dam, including the clay, the so called "Intze - wedge", was approximated with a discrete FEM-model. The piezometers were included as nodes of the Finite-Element-Mesh. The permeability of the materials (masonry, clay, rock) were assigned on the basis of hydraulic 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 (Fig. 3).

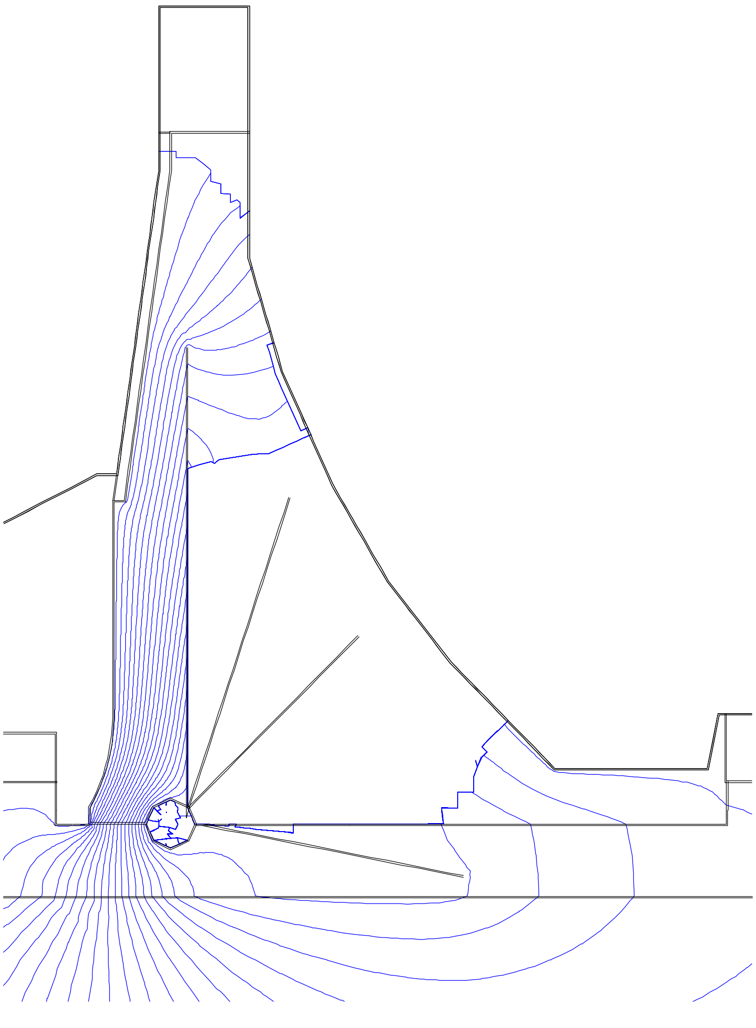

Figure 3. Potential lines of the field of water pressure at full reservoir

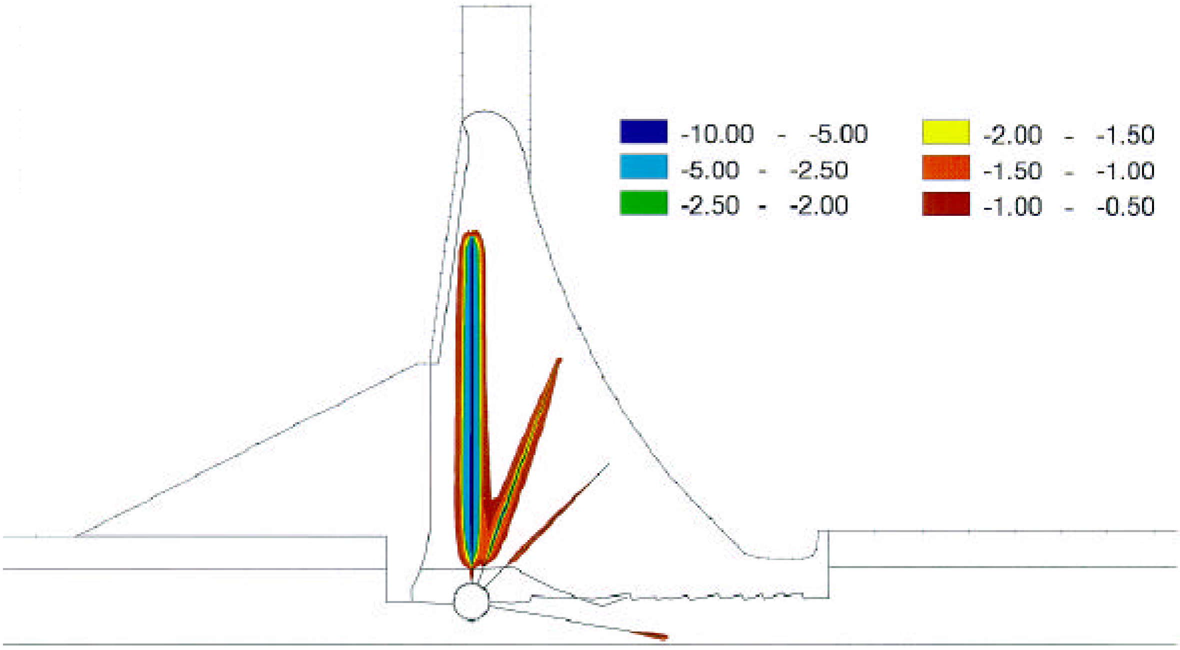

Figure 4. Differences of pressure between the profile where the drainages are located and the profile between the drainage drillings

Substantial constituent of the model investigation was the proof of the laminar effect of the vertical drainage drillings, which are arranged as fan in the distance of 4 m. For this a three-dimensional FEM-model of seepage was created. Figure 4 clarifies the calculated differences of pressure between the profile in that the drainages are located and the profile between the drainage drillings. The laminar effect is proven by the fact that the differences of pressure are significant only in a close range along the drillings.

3.2 *FEM-model of temperature flow*

For the calculation of the temperature flow a FEM-model was created, which was situated on the same profile as the seepage-model. For the calculation of the temperature flow by each material the three characteristic values - density, thermal conductivity and thermal capacity - were needed. While the density of rock, masonry and clay were well known, particularly the material dates necessary for the calculation of the thermal flow had to be inferred from the literature (Bettzieche, V. 1997a).

Table 1. material dates for the calculation of the temperature flow

material	density	thermal conductivity	thermal capacity
	g / cm³	W / (m * K)	kJ / (kg * K)
masonry	2,37	3,32	0,71
rock	2,70	3,00	0,43
clay (Intze-wedge)	2,00	1,20	1,38

Air and water temperatures were put in with their seasonal changes as boundary conditions at the specific areas of the dam surface as well as at the upper face of the Intze-wedge and the bedrock. The changing of the water level in the reservoir had to be considered as well.

For the Ennepe dam two scenarios were simulated

? mean annual variation of the temperature and
? rare temperature event extremely cold winter with an average period of 200 years (Fig. 5).

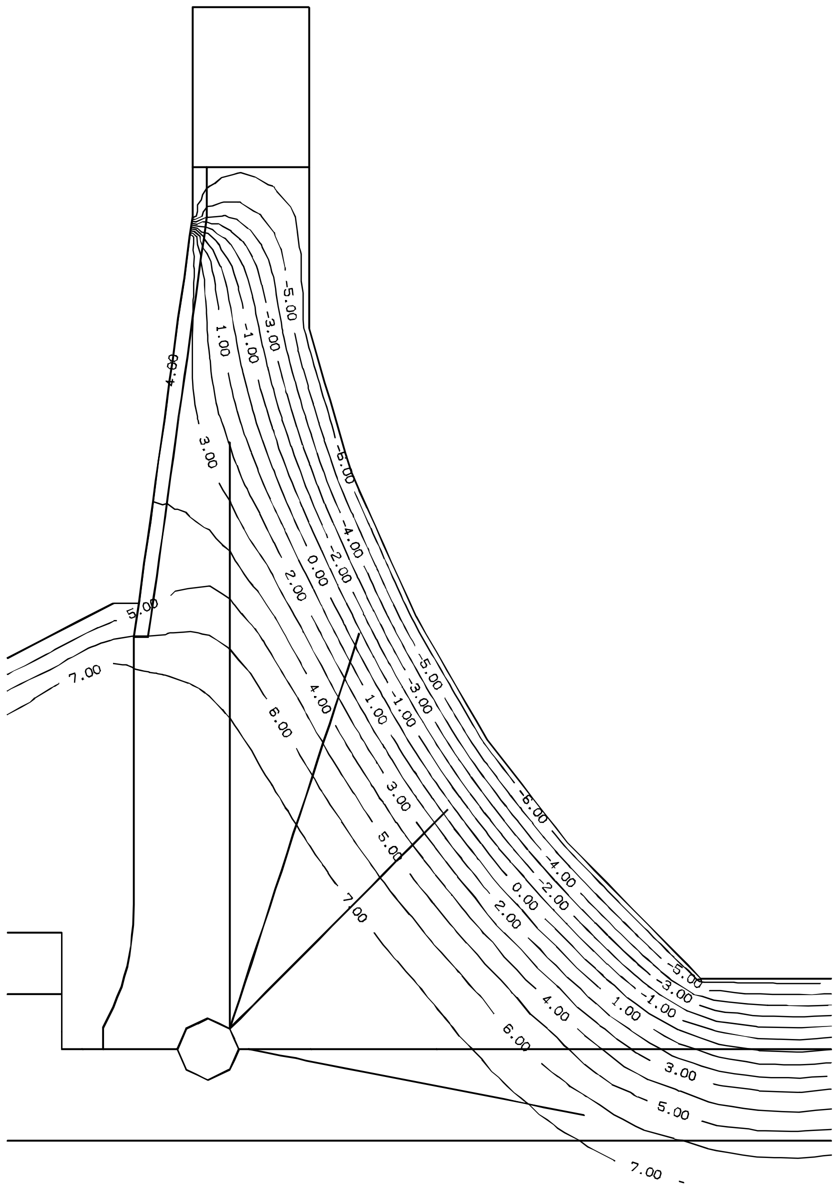

Figure 5. Temperature distribution (in °C) inside the dam at an extremely cold winter

3.3 *FEM-model of crack propagation*

In Germany the stability proof of a dam is to be done according to DIN 19700 section 11. This standard differentiates between three cases of calculation, for which several loads with different stages of the ground are to be combined. The cases I and III are usually most important (DVWK 1996).

In case I constant loads are to be considered. These are the water pressures from the full reservoir as well as changes of temperature and the dead loads. Usually the demand of the exclusion of vertical tensions or horizontal cracks at the water face of the dam becomes a crucial calculation criterion.

Case III regards extreme situations, like the overtopping of the dam crest during an extreme flood. In these rarely occurring situations a gaping joint up to the center of the dam is certified. Since the water will penetrate this joint, the appropriate water pressure in the joint must be considered (Bettzieche, V., et al. 2000a).

For the Ennepe dam the proof of stability was carried out accordingly. The effects of the water forces and temperature influences could be taken into account realistically on the basis the described simulations.

It was shown, that in winter the internal stresses of the concrete dam lead to a significant reduction of the pressure at the upstream side. In case I, at full reservoir, the internal temperature stresses as well as the tensions resulting from the water pressure at the upstream face of the dam almost reduce the pressure from the dead weight of the masonry to zero at the water side of the concrete dam. A fissure, crack or a gaping joint does not occur however.

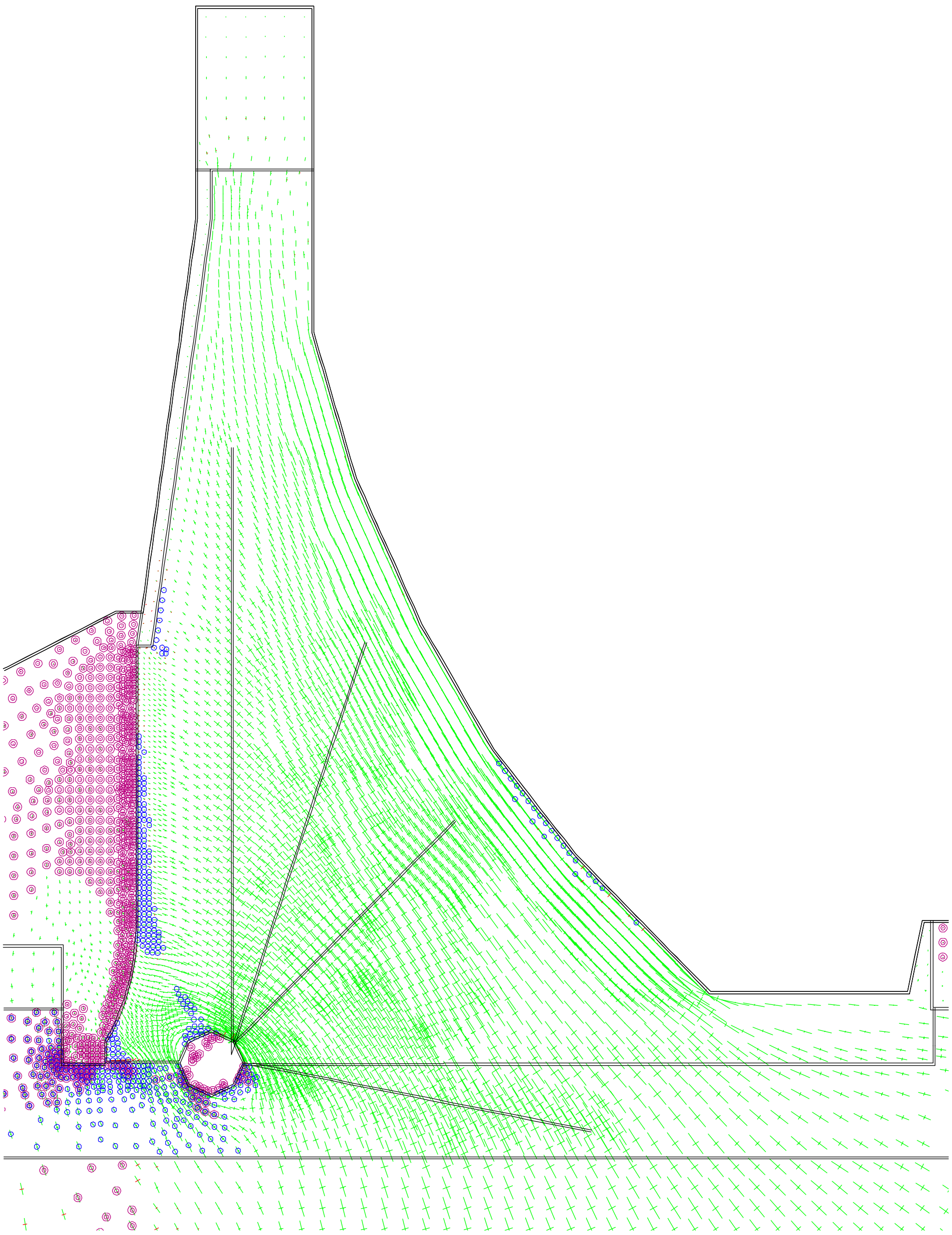

Figure 6. Main stresses (crosses) and regions with cracks (circles) inside the dam at an extreme flood

With an extreme flood of case III and according to higher water levels in the reservoir however vertical tensions at the upstream side of the dam occur. According to DIN 19700 these tensions are not allowed, so that the effect of the opening of cracks has to be examined. The fluid pressure field is influenced by the changing boundary conditions along the cracks. This "hydrofracturing" problem leads to changed loads and a renewed calculation and if necessary further iterations until a stationary status is achieved. If then the condition of gaping steady up to the centre of the dam is kept, the stability proof is essentially reached also for the extreme situation. This could be shown for the Ennepe dam (Fig. 6).

4 REHABILITATION

4.1 *Drainage Gallery*

The Ruhr River Association suggested the construction of the drainage gallery with a tunnel boring machine (TBM). This construction method was accepted by the Reservoir Supervision Authority. 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, Fig. 7),
? the length of the gallery of only 370 m, being unfavourable for the economical use of a TBM

This demanded the use of a small and manoeuvrable tunnel boring machine like the Robbins 81-113-2 TBM by the Murer AG from Switzerland. This TBM is equipped with only one pair of grippers. Therefore this TBM is extremely manoeuvrable.

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.

4.2 *Dam Section for Experimental Measuring and Monitoring*

It has been mentioned, that before the execution of final stability calculations the effects of the drainage measures on the pressure conditions inside the dam and the bedrock had to be investigated by experimental measurings in a specific section of the dam. The results of these measurings were supposed to be the basis both for the determination of the distances between the drainage fans and for improved elastic moduli. For this reason a specific section for experimental monitoring with a length of 40 m was laid out in the centre of the dam. After the completion of the gallery this section was equipped with measuring devices, making use of the easy access via the gallery itself.

The layout scheme of the drainage borings, as one of the most important assumptions, had to be checked. The numerical calculations led to a provisional distance of 4 m between the drainage fans. It had to be examined, if this distance was sufficient for a reliable reduction of the uplift pressure inside and underneath the dam.

According to the german Guidelines (DVWK 1991) the following measuring devices have been installed (Fig. 7):

? 2 plumblines, l = 50 m (from the crest to the gallery),
? 2 invert plumblines, l = 25 m (in continuation to the plumblines),
? 2 inclinometers for monitoring of possible movements of the crest
? 2 measuring sections with 9 piezometers each, in order to monitor the piezometric pressures from the upstream to the downstream face of the dam (Fig. 8).
? 2 measuring sections with 40 temperature gauges together and an additional fibreoptical sensor (Bettzieche, V. 1997b).

Since the Ennepe Dam was supposed to be run without a steady operating crew, all relevant data of the structure are provided for external monitoring via a data transmission system.

5 A POSTERIORI PROOFING AND RESULTS

Additionally to the measurements of the described measuring instruments the seepage was measured, which flowed out 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. 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 from same order.

The measured values prove the tightness of the masonry dam, which is substantially higher than assumed. The permeability of the rock corresponds to the assumption.

Table 2. 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	0,297
70° drains (2)	0,5	0,012
45° drains (3)	0,1	0,001
ground drains (4)	0,7	0,035
surface of the gallery	7,2	3,846

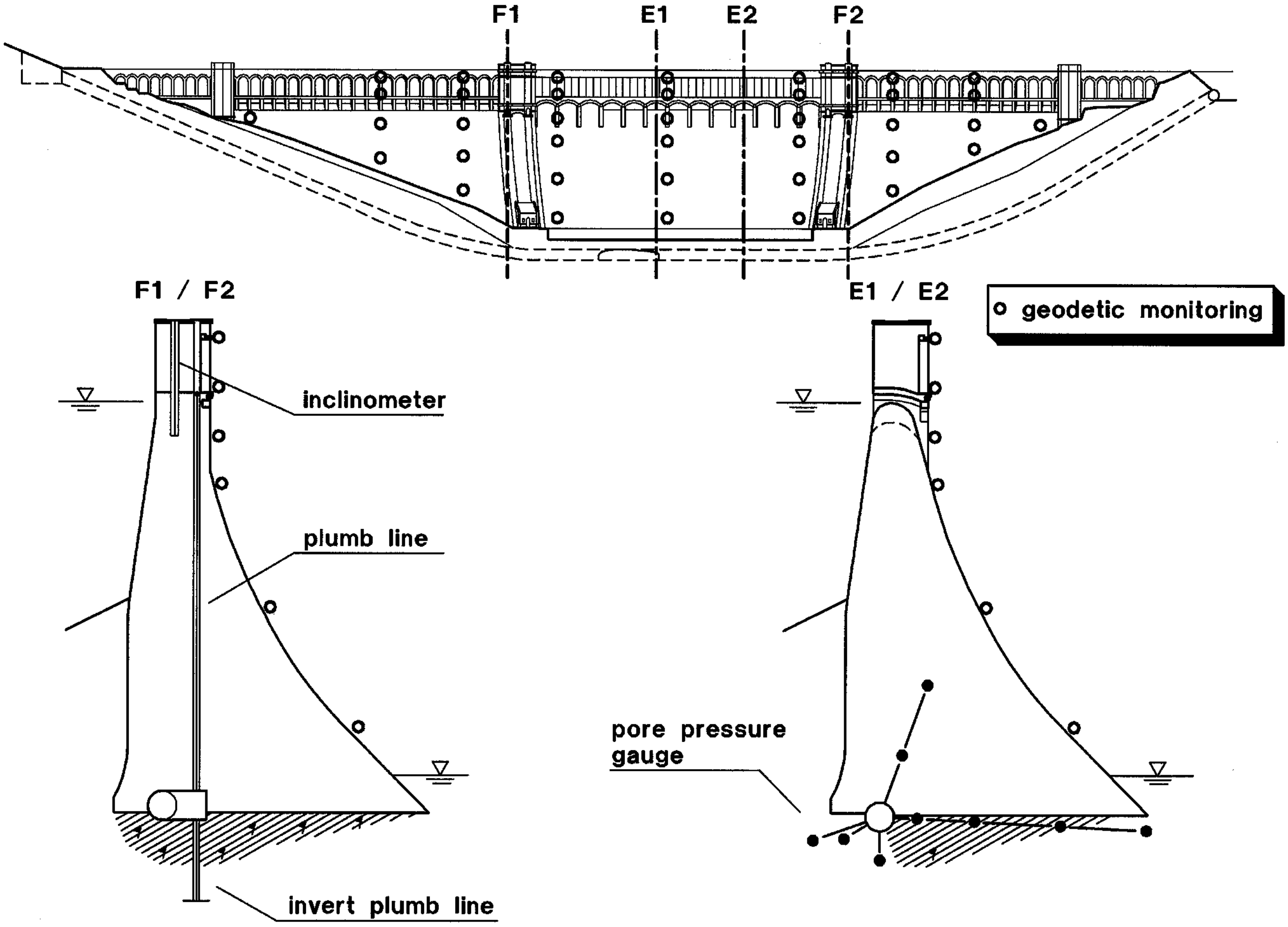

Figure 7. Measuring Equipment for the Experimental Section (incl. Geodetic Monitoring System)

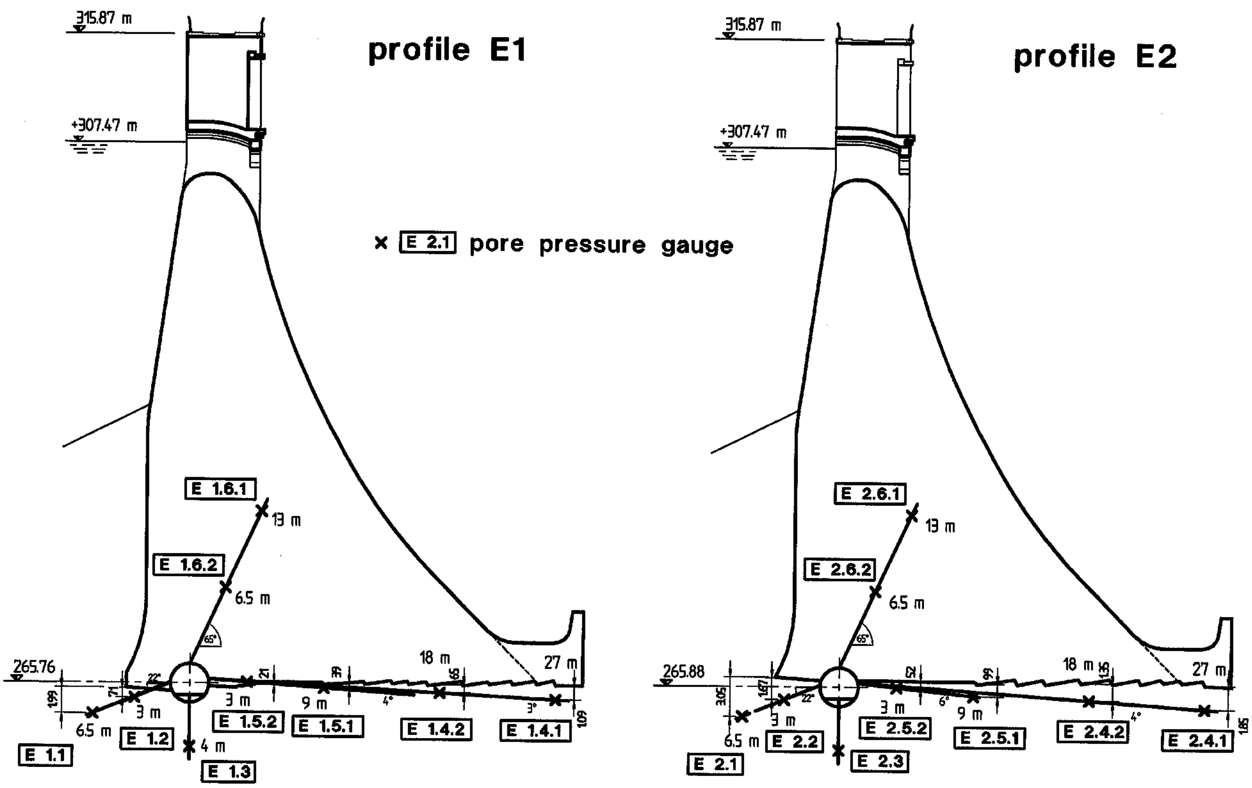

Figure 8. Measuring sections E1 and E2 with piezometers

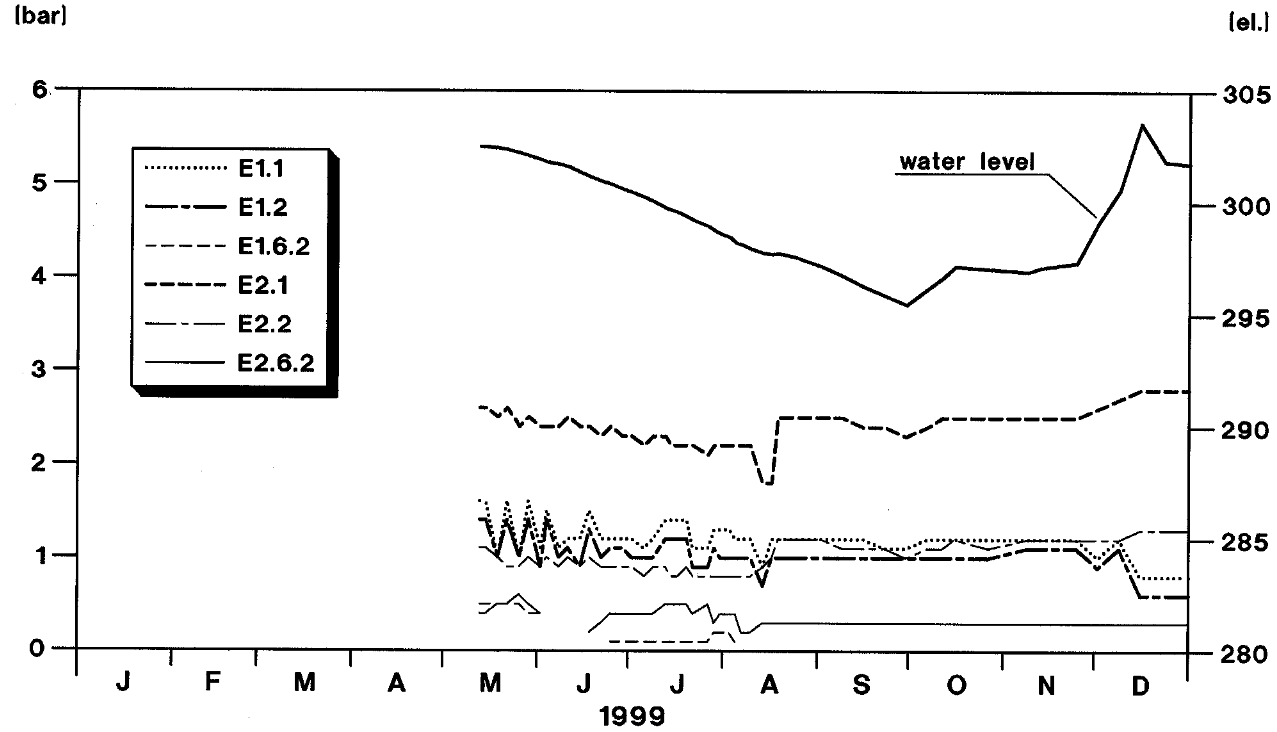

Figure 9. Measurement of porepressure (only measurable devises plotted)

Also the measurements of porepressure were analysed constantly and verify the success of the rehabilitation:

1 The masonry body of the dam is substantially drier than assumed in the seepage computations and in the structural investigation (Table 2). A considerable pore water pressure does not exist inside the dam. Only the piezometers located at the upstream side show measurable pressures (s. Fig. 9).
2 Under the upstream face of the dam a fast reduction of uplift pressure takes place.
3 The drainage gallery itself provides an extensive drainage of the dam and bedrock. Together with the permeable upper rock horizon it reduces the sole water pressure and the water pressure in the bedrock.
4 The masonry dam was substantially relieved from the water by the mechanism of drainage curtain.
5 Altogether the measurements corroborate the success of the rehabilitation and the assumption of the uplift at the a-priori calculations.

These results were confirmed also in the further observations. The comparison of the results of measurement with the assumptions of the (a priori) simulations the success of the rehabilitation of the Ennepe dam and serves as basis of the dam monitoring in the next years of operation.

6 CONCLUSIONS

The 100 years old Ennepe dam had to be adapted to the established technical standards. By numeric simulations and measurements as well as a new procedure for the propulsion of the drainage gallery the costs of rehabilitation could be bisected of 40 millions EUR to 20 millions EUR.

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