Experience with subsequently installed Drainage Systems inside of Masonry Dams

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ABSTRACT: At the Beginning of the 20th century many masonry dams with build-in drainage systems were constructed in Germany. Several circumstances caused the malfunction of these systems after more than 60 to 90 years in operation. In 1965 The Ruhr-River-Association started the rehabilitation of these dams by blasting a drainage gallery into the dam of the Lister Reservoir. From 1997 to 1998 the Ennepe Dam was reconstructed by mining the drainage gallery with a tunnel boring machine (TBM). The rehabilitation concept was based upon a detailed feasibility study, applying different numerical simulation methods. The official permission required the proof of the performance of the structure by several measurements. The comparison of the real measurings with the assumptions from the "a-priori"-simulations proves the successful rehabilitation and is a valuable tool for reservoir monitoring in the next years of operation.

1 INTRODUCTION

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.

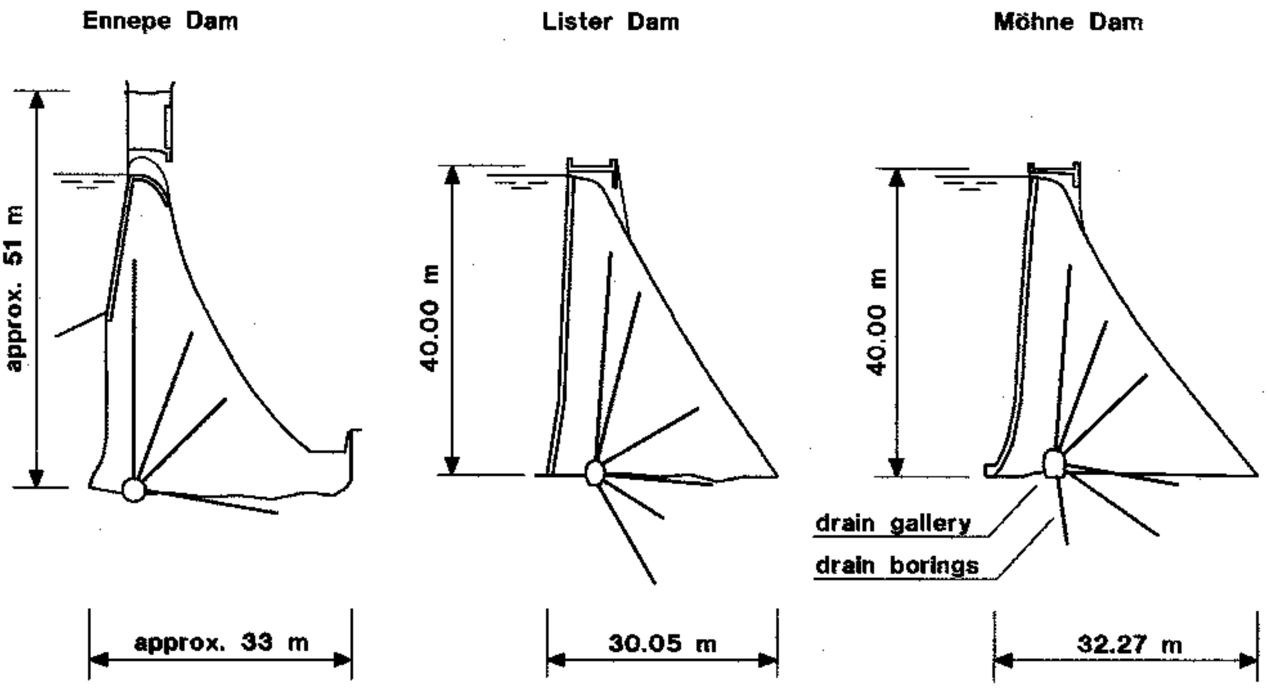

Figure 1. Masonry dams of the Ruhr-River-Association, rehabilitated with drain systems

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 joints, as well as drainage system for increased water pressures.

2 INVESTIGATION OF THE EFFECTS FROM DRAINAGE SYSTEMS AT THE ENNEPE DAM

In June 1997 the 93-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. 2) 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.

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 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).

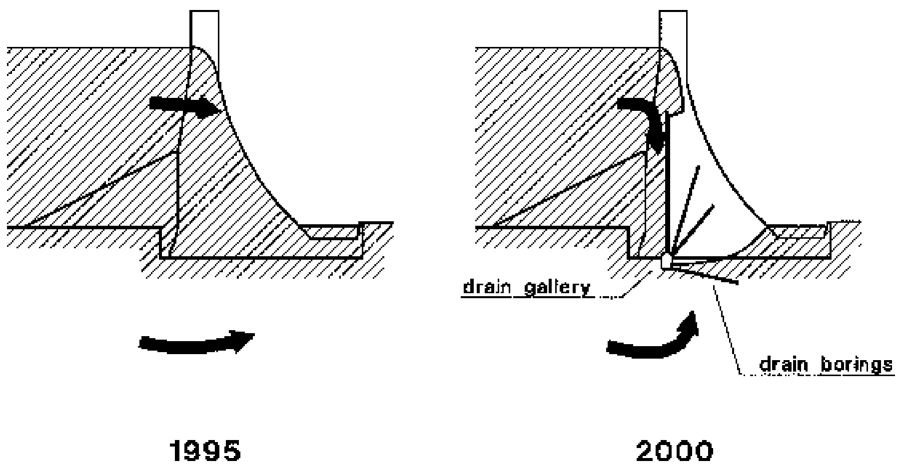

Figure 2. Realised concept of rehabilitation, using draining at the Ennepe Dam

2.1 *A-priori Studies of the Drainage System*

For the optimization of the arrangement of the drainage borings as well as of the planned measuring instruments a three-dimensional 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).

Two exemplary cross sections were provided as 3D-modells. The first cross section represents the situation in the middle of the dam. The inspection gallery is placed half part in the masonry and half in the bedrock.

The second cross section figures the situation where the inspection gallery is placed some meters below the foundation, completely surrounded by the bed rock (this is not shown here).

With both models different distances of the arrangement of the drainage borings were examined on their drainage effect. The drainage is fan-like arranged, by implementing each fan in a cross section. A fan consists of four drillings, which were finally implemented as follows:

- drilling D1, perpendicularly upward (90° to the downstream face), depth: 28 m
- drilling D2, diagonally upward (70° to the downstream face), depth: 20 m
- drilling D3, diagonally upward (45° to the downstream face), depth: 15 m
- drilling D4, diagonally downward (-10° to the downstream face), depth: 17 m

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 is formed below the crest. Nevertheless the quantities of seepage through the masonry are 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 the through 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 ranges nearly to the inspection gallery.

Fig. 4 shows the situation of seepage in two horizontal sections. The first section is placed at the middle of the height and cuts the first drain boring. The second section is placed 10 m above the gallery and cuts all three dam drainages. In both sections the largest potential dismantling takes place in the small range between the upstream face and the layer of the first drain boring. Approximately 3 m behind the drainage layer no more changes of the potential field are noticed.

Fig. 5 represents the differences between the pore pressure in the section of the drainage fan and the section between two fans. At a distance of 1 m from the first drain boring the differences of pore pressure are not more than 1 m, a very fast pressure equalization takes place between the fans from the upstream to the downstream side. This effect was observed with a distance of 3 m and 4 m of between the drainage fans. The differences of pore pressure between this two layouts are shown in Fig. 6.

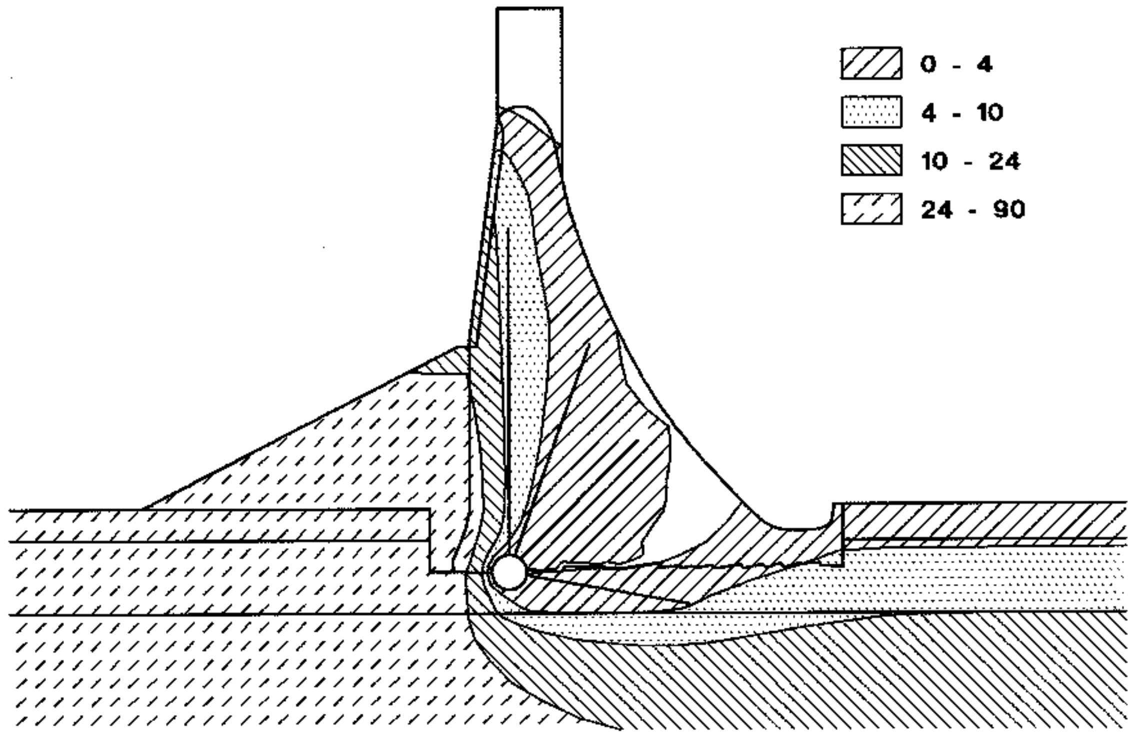

Figure 3. Seepage in a cross section of the Ennepe Dam (water pressure in m)

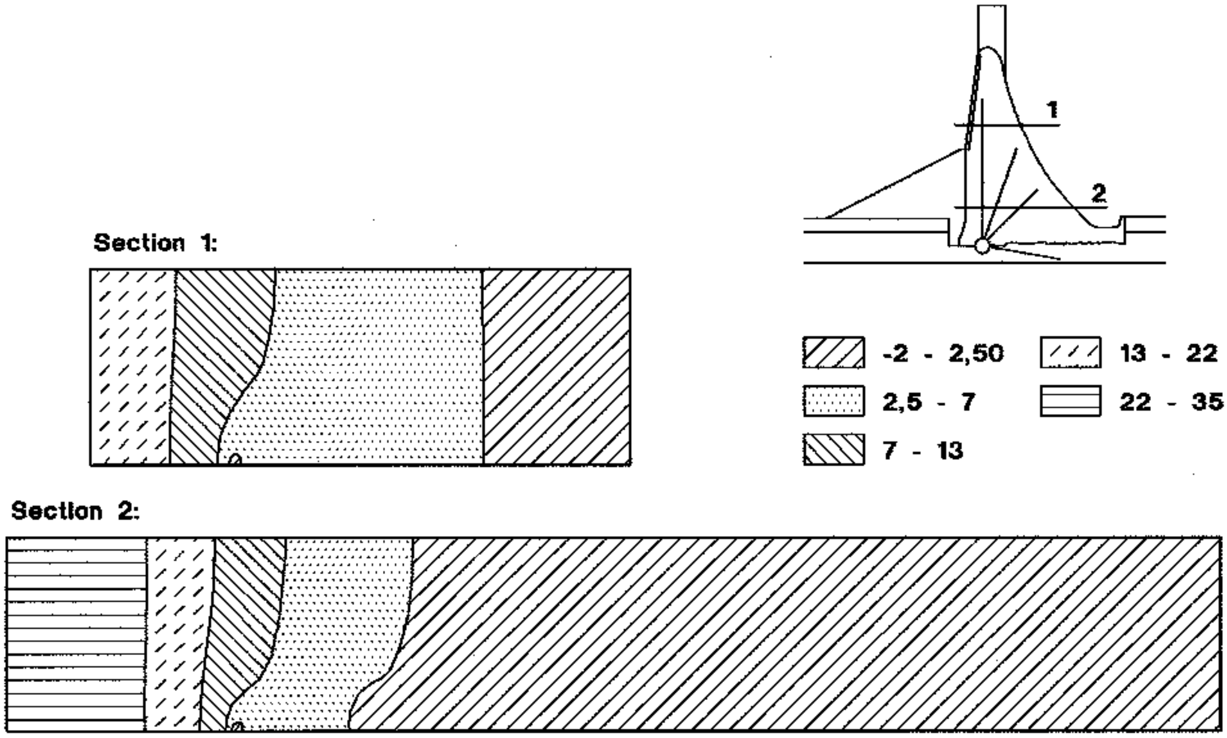

Figure 4. Seepage in two horizontal sections of the cross section model (water pressure in m)

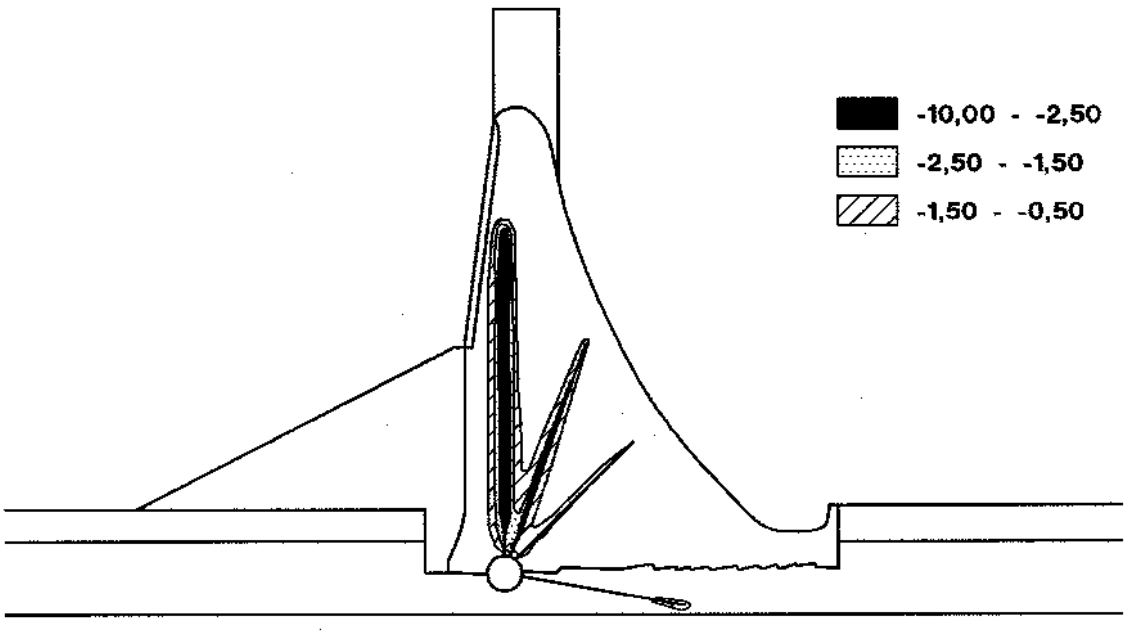

Figure 5. Differences between the water pressure (in m) in the section of the drainage fan and the section between the fans

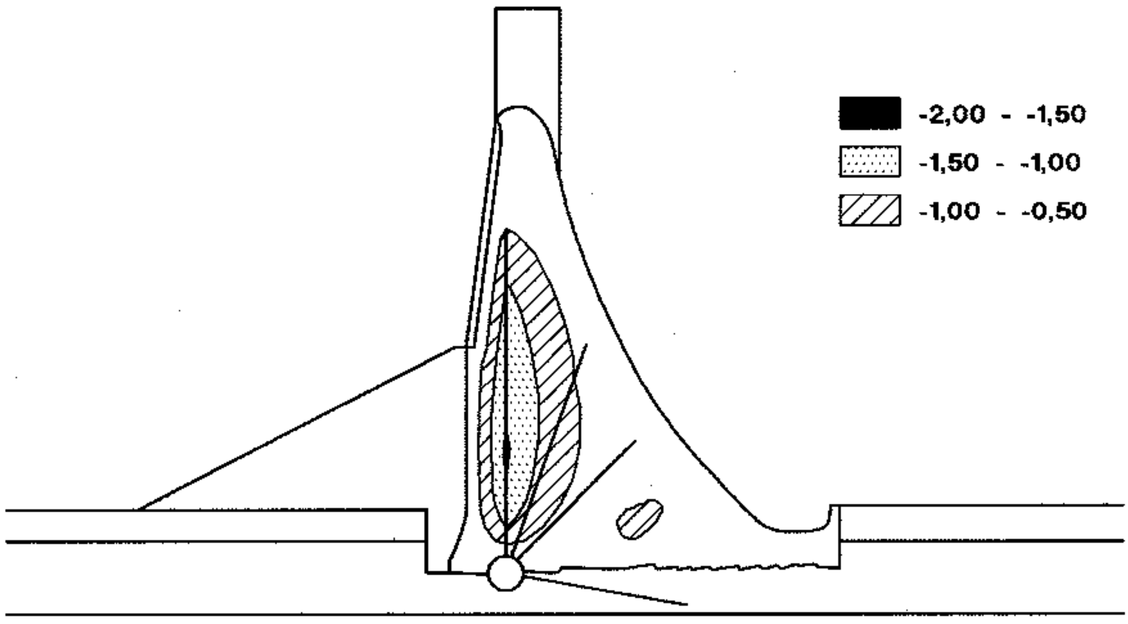

Figure 6. Differences of water pressure (in m) between the models with 3 m and 4 m distance of the drainage fans

2.2 *Calculation of the Stability of the Dam*

The rehabilitation concept was based upon a a-priori calculation of the effects from the drainage system to the dam stability. 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 (see above)
- a FEM-model of temperature flow 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

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.

2.3 *Rehabilitation of the Ennepe Dam*

2.3.1 *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),
- 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.

2.3.2 *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.

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

- 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. 2000b).

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.

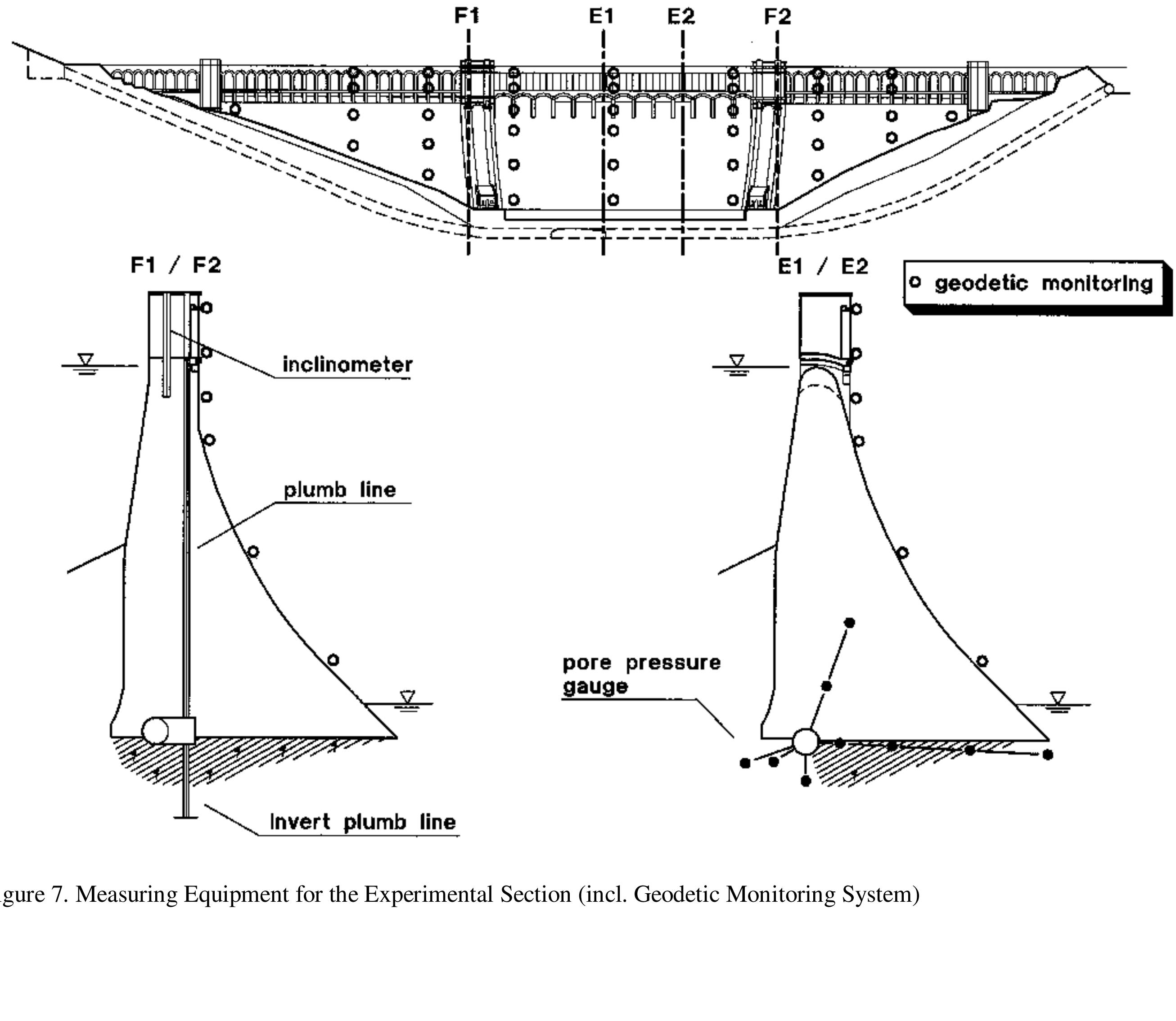

Figure 7. Measuring Equipment for the Experimental Section (incl. Geodetic Monitoring System)

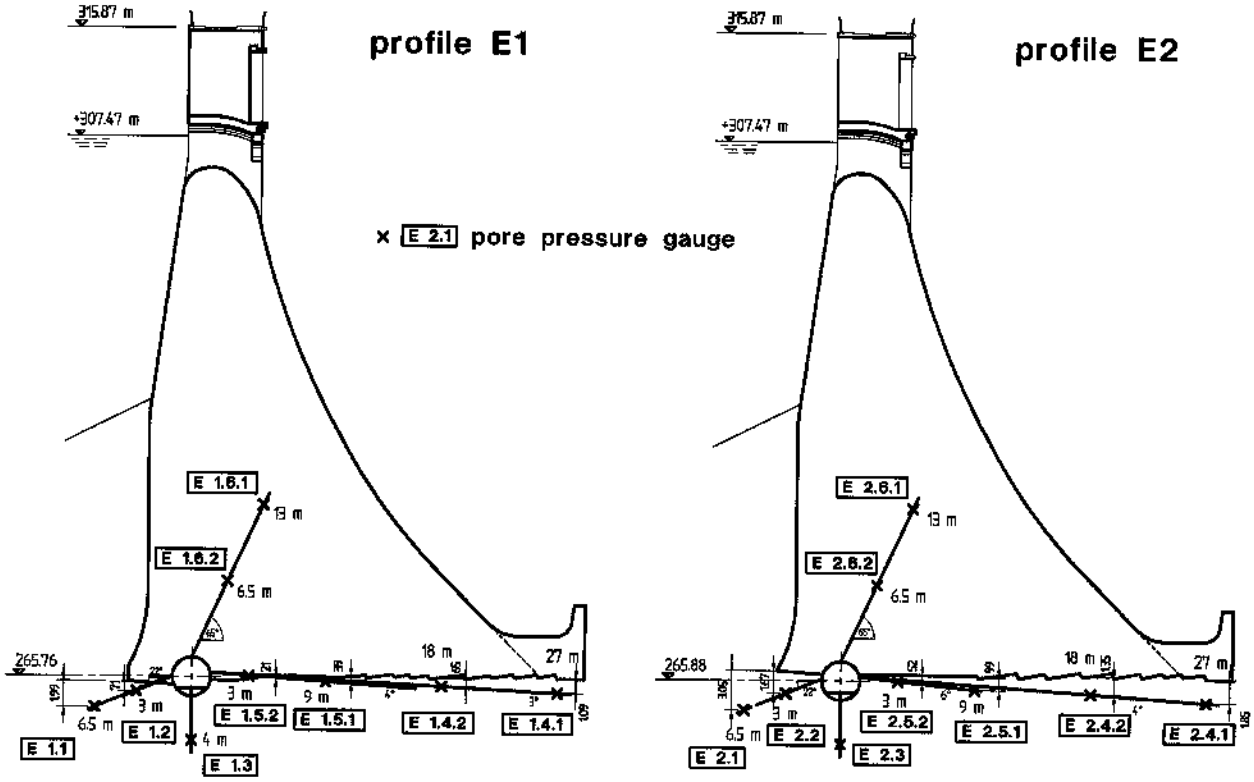

Figure 8. Measuring sections E1 and E2 with piezometers

2.4 *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.

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	0,30
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

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 2). 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.

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.

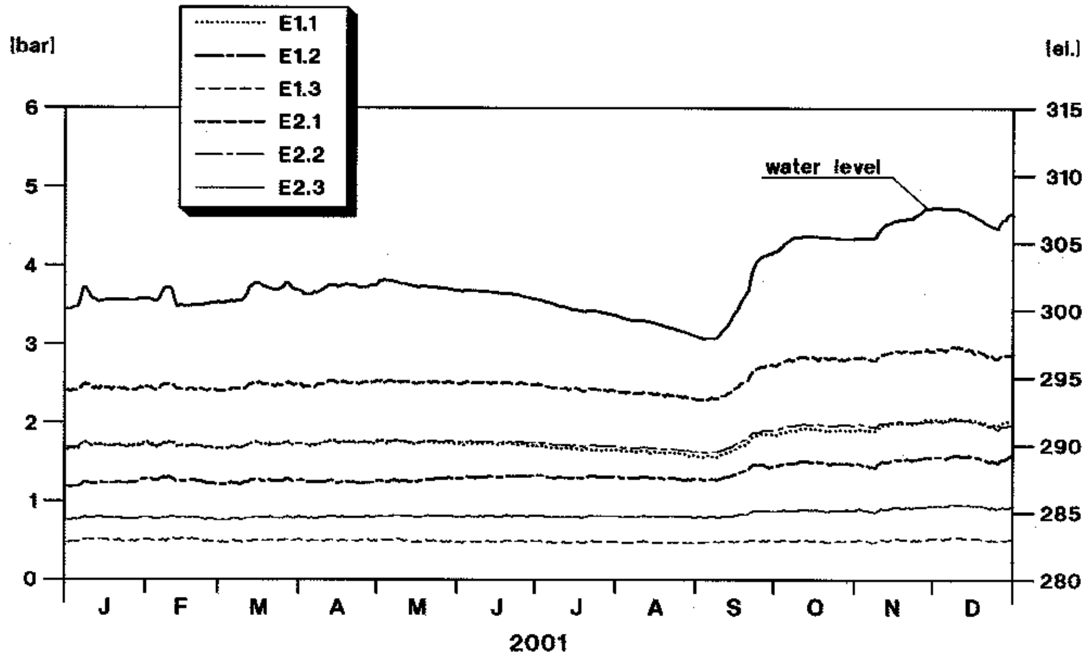

Figure 9. Measurement of porepressure (only measurable devises plotted)

3 EXPERIENCES IN MAINTENANCE

As there are no experiences about the maintenance of the new build drainages of the Ennepe Dam, it can only be reported on the drainages of the Lister and Moehne Dam (s. table 3). These two drainage systems are in operation for more than 25 years. The diameter of the drillings proved as sufficient for control and maintenance purposes.

At the drainage of the Lister Dam no maintenance work has been necessary so far. The drainage borings of the Moehne dam are regularly cleaned every second year with high pressure water jet. The experiences predominantly showed very small incrustations.

Table 3. Data of the drainage systems of three masonry dams (s. Figure 1)

	Ennepe Dam	*Lister Dam*	*Moehne Dam*
Dam Height	50 m	42 m	40 m
Crest length	320 m	264 m	650 m
Build/Rehabilitation	1904/1997	1912/1965	1913/1976
Number of drain borings/section (body/foundation)	3/1	3/3	3/3
Distance of sections	4 m	3 m	3 m
Diameter of drain borings	101 mm	60 mm	90 mm
Max. length of the vertical drain boring	28 m	30 m	24 m
Cleaning of the drain borings	not yet done	not yet necessary	every second year

4 CONCLUSIONS

Some 100 years old masonry dams had to be adapted to the established technical standards because their drainage systems had failed.

By numeric models the effects of later inserted drainage could be examined and optimized. The rehabilitation of the masonry dams took place via driving of a drainage gallery and bores from drainage. The planar effect of the vertical drain borings was of special importance.

The a-posteriori measurements verified the success of the rehabilitation.

At the Ennepe Dam the numeric simulations and measurements as well as a new procedure for the propulsion of the drainage gallery bisected the costs of rehabilitation of 40 millions EUR to 20 millions EUR.

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