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### TRINITY COLLEGE DUBLIN

*Reservoirs in a changing world*

## Rehabilitation of old masonry dams at full reservoir level - A comparison of successful rehabilitation projects

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**SYNOPSIS.** At the beginning of the last century about 40 gravity dams were built in Germany. During the last years extensive rehabilitation measures were carried out at several old masonry dams. Rehabilitation concepts which called for the construction of inspection/drainage galleries inside the dams turned out to be rather cost-efficient. Different methods for the construction of these inspection galleries were used – from manual driving of the tunnel to the drill & blast method and the use of a tunnel boring machine. The specific costs of these galleries varied, depending on the construction method.

### INTRODUCTION

During the first 20 years of the last century about 40 gravity dams were built in Germany (Figure 1). These structures were designed as so-called „Intze-type“ masonry dams with a curved base without any joints.

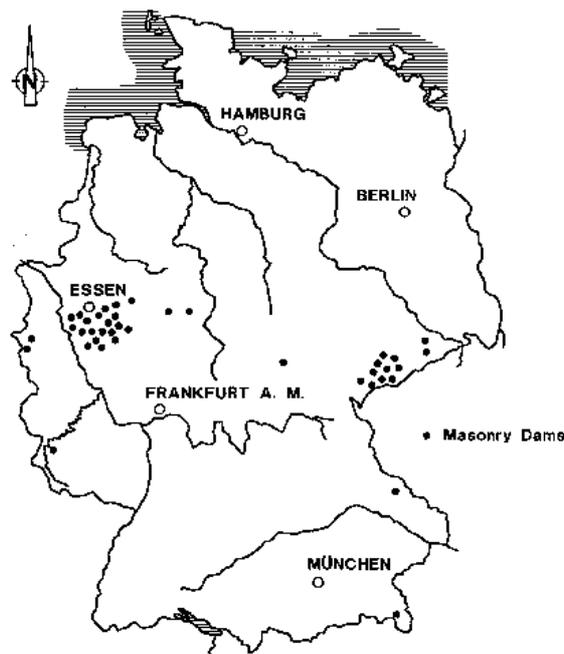


Figure 1. Masonry Dams in Germany

Hydraulic structures and dams are subject to ageing - like any other technical structure. The enormous importance of a reservoir for the infrastructure of the supply area and its damage potential require a continuing adaptation to the established technical standards. During the last years extensive rehabilitation measures were carried out at several old masonry dams.

The specific costs for rehabilitation varied from 40 € to 600 € per cubic metre of dam volume.

Rehabilitation concepts which called for the construction of inspection galleries inside the dams turned out to be rather cost-efficient. These galleries serve as means for the inspection of the condition of the foundation joints, as well as drainage system for increased water pressures and for the installation of monitoring equipment inside the dams. Different methods for the construction of these inspection galleries were used – from manual driving of the tunnel to the drill & blast method and the use of a tunnel boring machine. The specific costs of these galleries varied from 1.100 € per m<sup>3</sup> to 2.200 € per m<sup>3</sup> of gallery volume, depending on the construction method.

Three rehabilitations at the Fuerwigge Dam, the Gloer Dam and the Ennepe Dam are described.

Table 1: Dams data

	Fuerwigge Dam	Gloer Dam	Ennepe Dam
Year of completion	1904	1904	1904/1912
Height of Dam [m]	29	32	51
Length of Dam [m]	166	168	320
Volume of Dam [1000 m <sup>3</sup> ]	26	35	106
Storage Capacity [1000 m <sup>3</sup> ]	1670	2100	12600

## THE DAMS

The reason for the construction of the Fuerwigge- and Gloer-Dam was the expansion the activities of the steel manufacturing industry in the Sauerland mountain region during the late 19<sup>th</sup> century and its growing demand for a sufficient and reliable water supply for hydro energy purposes. Due to lack of water, the water mills and the affiliated manufacturing plants had to be shut off partly or completely for longer periods every year.

The Fuerwigge- and Gloer-Dam were built between 1904 and 1906 based upon the design of Prof. Intze. With dam heights of about 30 m and storage capacities of about 2 hm<sup>3</sup> they can be considered as small reservoirs.

The Ennepe Dam is a masonry dam with a length of 320 m and a height of 51 m and was built between 1902 and 1904 by the former owner, the Ennepe Water Association. Its main purpose was to stabilise the discharge of the Ennepe River, thus being a reliable source for the generation of

hydropower for the factories at the lower reaches of the river even in periods of drought.

Initially the dam was only 41.4 m high, which resulted in a storage capacity of 10.3 million m<sup>3</sup>. Between 1910 and 1912 a masonry block with a height 10 m was added to the crest of the dam. This enabled the former owner to raise the maximum water level by 2.5 m and created a storage capacity of 12.6 million m<sup>3</sup>.

#### Problems with these old masonry dams

Originally these three Dams were not equipped with an inspection- and drainage gallery. 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 dams. Unintentionally these drainage pipes had been filled with grouting material during several repair works in the 1950<sup>th</sup>. Thus during the last decades there was no effective drainage system available both in the dams and in their bedrock.

These old masonry dams were 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 adaptation of the Dams to the established technical standards. The maximum storage level had to be reduced for safety reasons at many old dams in Germany,

For different reasons the required adaptation some dams was not carried out until the 1990<sup>th</sup>. In June 1997 the Ruhr River Association took over the Ennepe Dam from the former owner, the Ennepe Water Association under the obligation to adapt the dam to the established technical standards and to carry out rehabilitation measures for the long term safety of the structure.

The Fuerwigge Dam is owned by the Ruhr River Association since 1933. Its refurbishment was postponed for the time being. The same goes for the Gloer-Dam, which is currently refurbished by the Ruhr River Association on behalf of the owner, the City of Luedenscheid municipal water works.

Specially the Ennepe Dam - as mentioned above - was built for the water supply of 170.000 consumers in the Ennepe-Ruhr District. Therefore during the rehabilitation process the reservoir could not be emptied without causing major problems. Former investigations show that a temporary conversion of the water supply system to other sources would cost about 13 million US-\$ and had only a slight chance for realisation therefore. The basic principles for the adaptation of the dam to the established technical rules had to take this into account.

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. First calculations showed that this would take about 40 Mio. €.

#### REHABILITATION CONCEPT "DRAINING THE DAM"

A concept for the rehabilitation of dams has been developed further by the Ruhr River Association, being used first time in 1965 at the rebuilding of the Lister Dam: 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.

Additional rehabilitation measures were carried out at all reservoirs e.g.:

- 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.

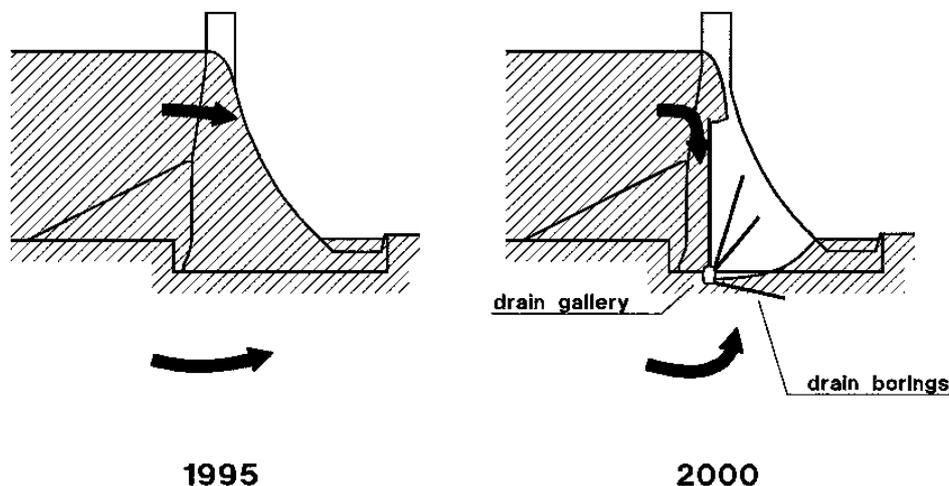


Figure 2. Realised concept of rehabilitation of the Ennepe Dam, using draining

The Reservoir Supervision Authority agreed upon the entire rehabilitation concept, under the reservation, that measurements had to prove the success of the rehabilitation.

### FEM-Model

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 concepts of rehabilitation.

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 (porepressure)
- 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 (Betzliche, V. 2000b)
- 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 (Betzliche, V. 2000a)

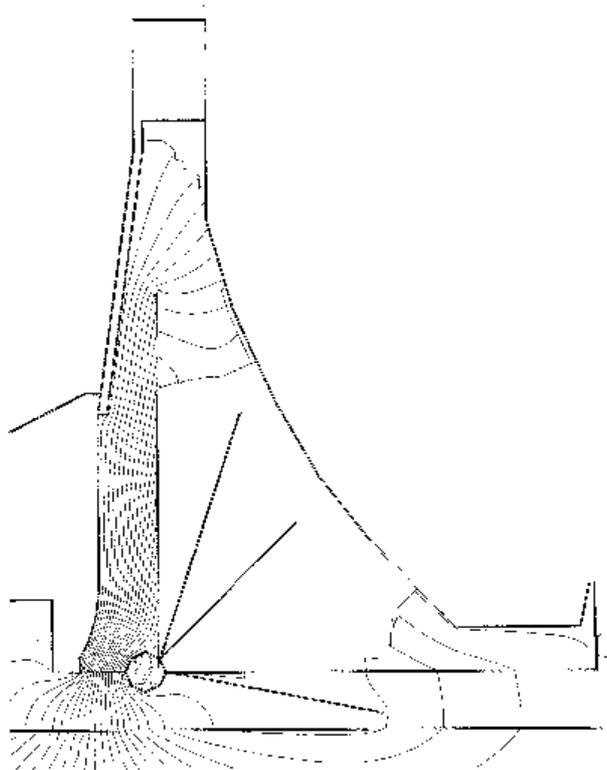


Figure 3: FEM-calculated field of porepressure

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 at the Ennepe Dam and 3 m at the Glör Dam. It had to be examined, if this distance was

sufficient for a reliable reduction of the uplift pressure inside and underneath the dam.

Table 2: Data of the Rehabilitation

	Fürwigge Dam (Concept)	Glör Dam	Ennepe Dam
Rehabilitation Concept	only borings	blasting a tunnel	tunnel boring machine
Length of the Gallery	0 m	45 m	430 m
Profile of the Gallery	no gallery	2,20 m x 3,00 m	Ø 3,00 m
Total Length of Drainage borings	900 m	580 m	1350 m
Costs of Drainage Gallery	- €	330.000 €	4.000.000 €
Costs of Borings	205.000 €	150.000 €	250.000 €
Costs of Injections	95.000 €	65.000 €	- €

The investigations at the Fuerwigge Dam indicate that a drainage gallery is not necessary. The rehabilitation concept calls for the installation of a fan of drainage borings only. These borings can be driven from the bottom outlet galleries, which cross the dam (s. Figure 4).

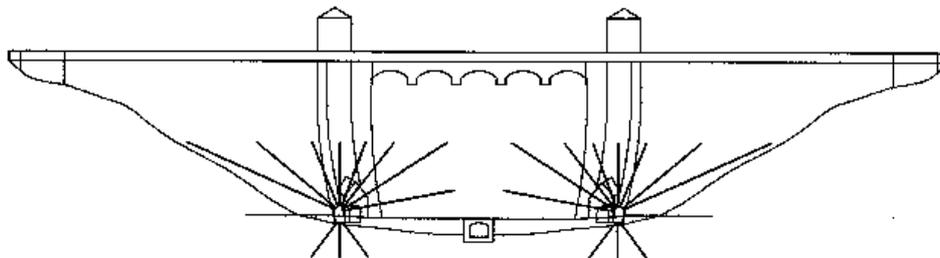


Figure 4. Drain Borings inside the Fürwigge Dam (Scheme)

#### Measurements

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 measurements (Betzliche, V. & Heitefuss, C. 2001).

At the Ennepe Dam i.e. the following measuring devices have been installed, according to the German Guidelines (ATV/DVWK 1991):

- 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.
- 2 measuring sections with 40 temperature gauges together and an additional fibreoptical sensor (Betzliche, 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.

#### REHABILITATION

General solutions for the rehabilitation of dams do not exist, but a wide variety of technical concepts. The choice of a rehabilitation concept requires the adaptation of the optimal technical and economical solution to the specific hydraulic structure.

During the last years some gravity dams were refurbished by the installation of an concrete diaphragm wall at the upstream face. This requires the complete drawdown of the reservoir, allowing a restricted water supply at the most. Additionally the sealing of the bedrock is necessary in order to prevent uplift pressures.

In many cases dams have been refurbished by a combination of grouting and drainage measures. For this purpose cement is injected through boreholes into the dam and the bedrock, reducing the permeability to a tolerable level. The sealing of the dam and the drainage of the bedrock reduces the uplift pressure. The drainage borings collect the seepage water in order to guarantee the prevention of excessive uplift pressures.

The construction of the boreholes requires the driving of a drainage- and inspection gallery at the upstream foot of the dam. These galleries with a width of 2 to 3 m and a height of about 2.5 m run through the dam longitudinally in the foundation joint.

These inspection galleries have been driven with various methods, for instance the manual driving, the use of a tunnel boring machine and the drill & blast-method.

#### Manual Driving of the Gallery

For the construction of the inspection gallery at the Unteren Herbringhaeuser Dam near the City of Wuppertal the manual driving was chosen (Aberle, B. & Hellmann, H. 2000). This method can be adapted to the local conditions very good. The precise contours and varying courses of the gallery can easily be driven. Masonry made of greywacke or material of similar strength allow only very limited rates of advance - often less than 0.1 m per work shift. The excavation of the masonry can be supported by cracking equipment and hydraulic jacks, even though the use of machinery is limited by the small cross sections of the galleries. The irritation by dust

and noise in the narrow galleries in combination with the heavy work during many months puts an enormous strain on the tunneling workers.

The strain on the tunneling crews can be reduced by the use of overlapping core drills. Due to the very limited rates of advance this method can be economically used only in very specific situations or at very short tunneling stretches like break-throughs.

#### The Drill & Blast - Method

The drill & blast - method has successfully been used by the Ruhr River Association in the 1970's for the driving of a longitudinal inspection gallery at full reservoir level at the Moehne Dam. During the last years inspection galleries were driven into several dams using the drill & blast-method. All projects showed, that this method can be adapted to every necessary geometry on site (Aberle, B. & Hellmann, H. 2000). Very steep slopes at the abutments, right-angled junctions and even shafts can be driven precisely. The very small distance of the inspection gallery to the upstream foot of the dam requires a very careful and rock-protecting blasting method. By protective blasting the vibration load and the weakening of the surrounding masonry can be limited.

Due to precise blasting these inspection galleries could be constructed economically with little additional work due to over- or underbreak. Almost every inspection gallery was constructed without final shotcrete or concrete linings.

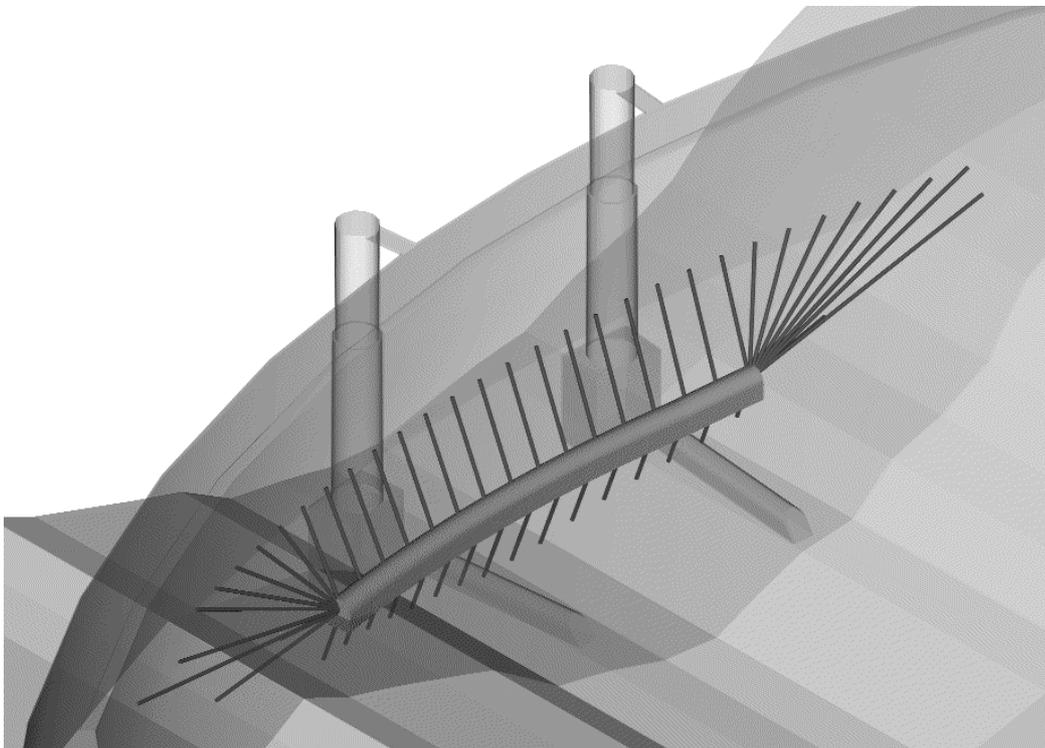


Figure 5. 3-D-CAD-View: Drainage gallery inside of the Glör Dam

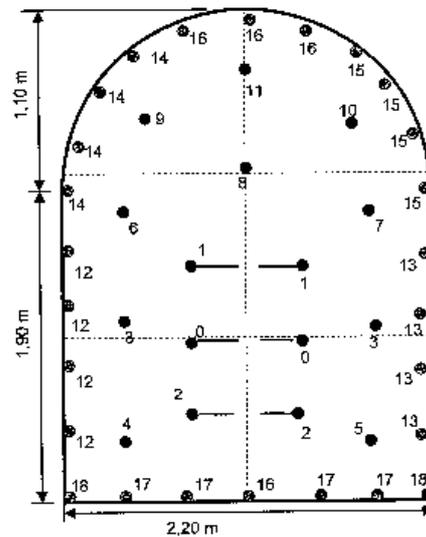


Figure 6. Blasting scheme of the drainage gallery of the Glör Dam

#### Use of a Tunnel Boring Machine

At the Ennepe Dam 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 (Heitefuss, C. & Rissler, P. 1999).



Figure 7: Tunnel boring machine

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,
- 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 comparatively 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.

#### PROOF OF THE SUCCESSFUL REHABILITATION

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.

At all dams 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.

#### COMPARISON OF THE CONSTRUCTION METHODS

Table 3 compares the described methods. The given values are based on the evaluation and on the experiences from the rehabilitation work at a number of dams. All given numbers are average values and have to be considered as a rough estimates.

It can be shown that the rate of advance per workshift and the unit price for the driving of one cubic-metre correlate. In case a TBM is used, major investments and deductions have more importance.

Table 3. Comparison of the construction methods

Method	TBM	manual*)	core drilling*)	blasting
Performance per worker and shift (WS)	1 m <sup>3</sup> / WS	0,4 m <sup>3</sup> / WS	0,2 m <sup>3</sup> / WS	0,7 m <sup>3</sup> / WS
Costs	1.300 € / m <sup>3</sup>	1.800 € / m <sup>3</sup>	2.200 € / m <sup>3</sup>	1.100 € / m <sup>3</sup>
Advantages	rapidly, less damage to the rock	flexible minor expenditure	flexible, minor vibrations	flexible, minor expenditure
Dis-advantages	only large diametres	dust and noise conditions for the workers	time consuming, expensive	accurate supervision needed

\*) s. Aberle, B. & Hellmann, H. 2000

#### COSTS AND CONCLUSIONS

The 100 years old Fürwigge, Glör and Ennepe dam had to be adapted to the established technical standards. By numeric simulations and measurements as well as new procedures for the propulsion of the drainage gallery the costs of rehabilitation could be reduced. Former solutions, as the use of a diaphragm wall (s. Figure 8) were neglected as rather expensive.

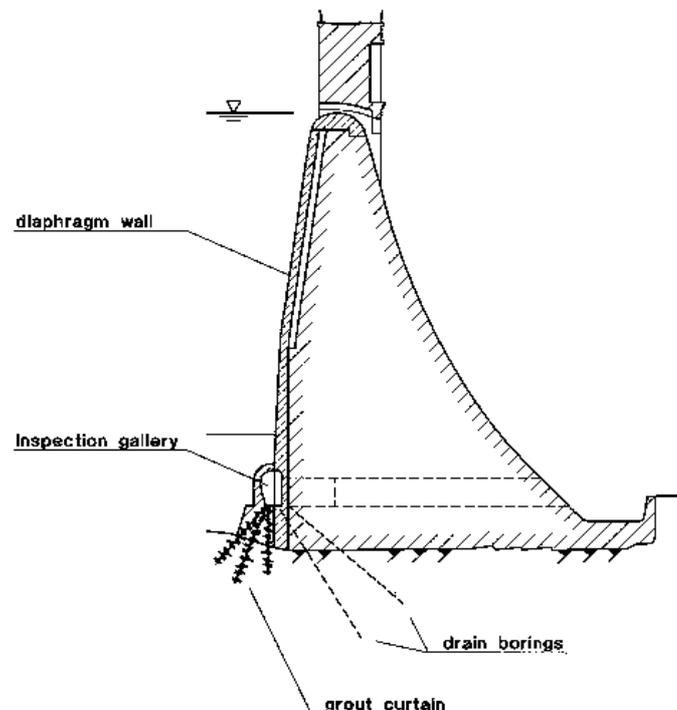


Figure 8. Earlier expensive concept, using a concrete diaphragm wall

At the Ennepe Dam the total costs of the rehabilitation could be bisected of 40 millions € to 20 millions €. This factor is also confirmed by the comparison of the rehabilitation of the Fürwigge, Glör and Ennepe Dam with other rehabilitations based on diaphragm walls, as shown in Table 4.

Table 4. Comparison of realised Rehabilitations (Total Costs)

Dam	Year of completion	Volume of Dam [1000 m <sup>3</sup> ]	Storage Capacity [1000 m <sup>3</sup> ]	Rehabilitation Concept	Costs per Dam Volume [€ / m <sup>3</sup> ]	Costs per Storage Capacity [€ / 1000 m <sup>3</sup> ]
Fürwigge (Concept)	1904	26	1670	only borings	62 €	0,96 €
Glör	1904	35	2100	blasting a tunnel	63 €	1,05 €
Ennepe	1904/12	106	12600	tunnel boring machine	189 €	1,59 €
Dreiläger	1912	85	4280	concrete diaphragm wall	177 €	3,50 €
Brucher	1913	27	3300		334 €	2,73 €
Fuelbecke	1896	17	700		350 €	8,57 €
Jubach	1906	27	1050		291 €	7,62 €
Hasper	1904	59	2050		304 €	8,78 €

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