Challenges and limits - the feasibility of underwater rehabilitation work

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SYNOPSIS. The bottom outlet facilities of many dams all over the world will have to undergo rehabilitation within the near future. Not only the early dams, built in the 19th or in the beginning of the 20th century are affected. Even large hydraulic structures, designed and built in the second half of the 20th century are faced with this problem. Due to various reasons a complete draw down of a reservoir for inspection and rehabilitation purposes has to be considered as not feasible in most cases. That requires manned or unmanned underwater inspection and rehabilitation techniques at the submerged structures of a dam. The paper describes the experiences gained during the underwater rehabilitation activities of the Ruhr River Association and how these experiences can be applied to other projects in Europe at water depths between 20 and 120 meters.

INTRODUCTION

The layout of many hydraulic structures all over the world does not make provisions for repair works of the bottom outlet facilities. This is not only the case for the dams of the very early design periods around the beginning of the 20th century. Even many owners of large hydraulic structures, designed and built in the second half of the 20th century have to face this problem.

At the early design periods the complete draw down of a reservoir for repair purposes was usually considered possible. Therefore the original design of that time did not make provisions for underwater inspection and repair work. Nevertheless even some modern dams have design deficiencies related to inspection and rehabilitation as well. The lack of support structures for emergency gates for instance turns out to be a major problem. Safe working conditions for the diving crews can not always been taken for granted.

Long-term benefits and performance of dams. Thomas Telford, London, 2004

LONG-TERM BENEFITS AND PERFORMANCE OF DAMS

Nowadays, due to possible restrictions for water supply, hydropower generation, irrigation, leisure activities and due to the risk of severe ecological problems in and around the water body of a reservoir a complete draw down for inspection and rehabilitation purposes has to be considered as impossible in many cases. Therefore rehabilitation works have to be done during full or partial operation respectively maximum or reduced reservoir levels which allow an unrestricted supply of water, depending on the various purposes of the reservoir.
Extensive underwater work has been done at the reservoirs of the Ruhr River Association (in German: Ruhrverband). These reservoirs provide bulk water for the industry and about 5 million people in the Ruhr area and cover a design and construction period from the beginning of the 20th century until 1966. During the life cycles of these reservoirs of up to one century quite a number of structural and operational deficiencies became evident, not to mention the regular ageing processes. Therefore during the last 10-15 years extensive rehabilitation measures were carried out at the reservoirs of the Ruhr River Association, mainly in order to refurbish the bottom outlet facilities and to adapt the existing hydraulic structures to new operational needs at reservoir levels which allowed an unrestricted water supply. In the following the experiences gained during the underwater rehabilitation activities of the Ruhr River Association are described.

The rehabilitation strategies of the bottom outlet structures of every dam were based upon the following ideas:

- to move the new intakes upstream, away from critical and narrow cross-sections at the upstream foot of the dam
- to use the new intakes as support structures for emergency gates
- to replace the old gates
- to install new intake gates respectively guard valves

Every project led to new experiences in underwater rehabilitation technology, which is described in the following.

Some experiences have been shared with other dam owners in Europe, responsible for reservoirs with water depths between 20 and 120 meters.

UNDERWATER REHABILITATION CASE HISTORIES

The Moehne Dam

Figure 1. Aerial View of the Moehne Reservoir

Introduction

The Moehne Dam (Figure 1) was built from 1908 - 1912 as a curved masonry dam with a height of 40 m, a length of 650 m and a maximum storage capacity of 134.5 million m³. The Moehne Dam was considered as one of the largest dams in Europe of that time. It became known world-wide, when during World War II the dam was severely damaged by an allied bomb attack. The dam was destroyed to a height of 23 m and over a length of 77 m. The following flood wave of about 110 million m³ of water and a height of 6 – 7 m killed more than 1.200 people and devastated the Moehne Valley.

The concept for the rehabilitation of the Moehne Dam

The rehabilitation of the bottom outlets of Moehne Dam can be considered as the first milestone in underwater rehabilitation of the dams of the Ruhr River Association. The work started in 1992 and was finished in 2002. It has been described in (Heitefuss & Kny 2002) and (Klein, Harder & Klahn 2003). Nevertheless two important aspects of underwater work are worth to be mentioned.

Underwater concrete work

After the installation of the new pipework one of the final steps of the construction of new support structures for the emergency gates is usually the underwater concreting. It took various test pourings, until the optimal recipe for the underwater concrete was found. What has been an enormous problem during the Moehne project, turned out to be much easier at the next underwater rehabilitation projects, since there has been a remarkable advance in underwater concrete technology during the last ten years.

Use of a diving platform

When the rehabilitation work started at the Moehne Dam in 1992, this was also the start for the use of a special diving platform (Figure 2) which has been developed by the diving contractor in co-operation with the Ruhr River Association.

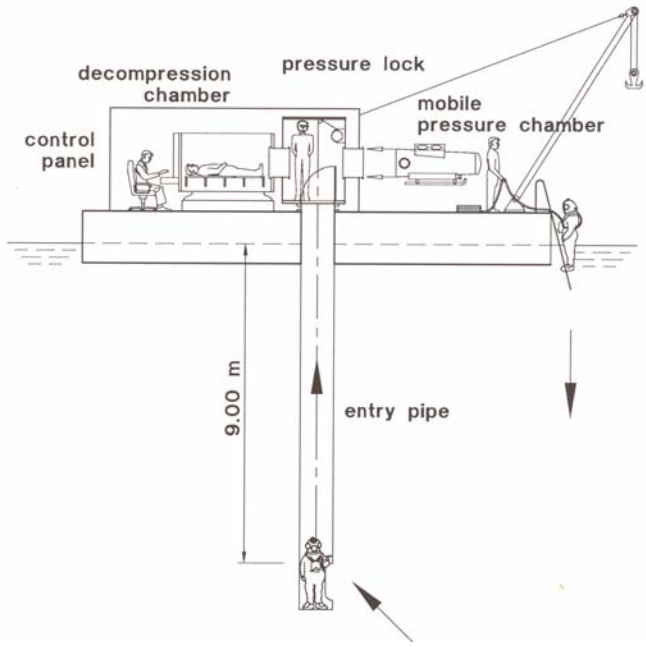

Figure 2. The diving platform with pressure chamber and entry pipe

This diving platform has proven to be a valuable tool for safe diving works at the construction sites of the Ruhr River Association for more than ten years. No diving accident worth mentioning occurred during this time.

The diving platform is equipped with two coupled decompression chambers, which are connected directly to a vertical entry pipe. This pipe reaches 9 m under the water surface and can be filled with compressed air. Thus, the diver can enter the pipe after his diving mission. He remains under pressure, disconnects the umbilical and can take off his diving mask or helmet. With an elevator he is lifted to a pressure lock, where he is undressed by an

assistant. Then he enters the decompression chamber for the reduction of pressure. This equipment allows the controlled decompression under dry and warm conditions, which both improves the decomposition of nitrogen in the divers body and prevents, that the diver catches a cold. This improves the safety for the diving crew and increases the effectiveness, since health problems of the divers are getting reduced.
Another technique to improve the effectiveness of the diving activities is the use of oxygen breathing masks in the decompression chamber. If the decompression has reached 0.6 atmospheres and less, the diver breathes pure oxygen in order to accelerate the nitrogen decomposition. According to the new German Safety Codes for Diving, the additional use of oxygen breathing gas extends the so-called ground time for instance at water depths between 30 and 40 meters up to 50 or even 60 % in comparison to the use of a regular breathing gas mixture inside the decompression chamber. Thus, at a water depth of 33 m the diver has a ground time of 80 minutes and a decompression time of 65 min.
The platform is also equipped with a mobile pressure chamber, which can be connected quickly to the pressure lock. In case of a diving accident there are two options. The diver is either placed in the mobile pressure chamber and brought to a hospital via truck or airlift within 30 minutes or medical assistance can be brought in via the second pressure chamber, which in this case is used as a pressure lock.

The Verse Dam

The Verse Dam is a multi-purpose reservoir with an earthfill dam with a concrete cut off and a height of 52 m.. Based upon the experiences from Moehne Dam the intake structures of Verse Dam underwent rehabilitation from 1995 - 1997. This work has been described in (Heitefuss & Kny 2002 / 1997).
At this project it proved, that a preliminary hydrologic study can be a valuable tool for an economical rehabilitation measure.
Before work began, a minimum reservoir level had to be found, which could guarantee the safety of water supply for the adjacent cities and allow reasonable and economical diving and decompression times for the diving crews. The calculations resulted in a minimum water depth of 38 m during underwater work, compared to a regular depth of more than 50 m. Thus the ground time of each dive was doubled.

The cost of the entire rehabilitation project amounted to nearly 2 million €. The cost of supply of steel (RSt 37-2) for the pipe-work and shield was about 8 € per kilogram. The additional cost for the installation of the pipe-work was about 14 € per kilogram of steel.

Figure 3. Aerial View of Ennepe Dam

The Ennepe Dam

The Ennepe Dam (Figure 3) is a curved masonry dam with a length of 350 m and a height of 50 m. It was built during the 4 years earlier than the Moehne Dam, based upon the same design principles. The concept for the rehabilitation of the entire bottom outlet structure was applying the techniques, which had already proven their feasibility at the Moehne and Verse Dam. In fact there was an additional challenge for the engineers of the Ruhr River Association, because it was necessary to install new intakes for bulk water at different water levels (Heitefuss & Kny 2002 / 2001).
Another major difference to the rehabilitation projects at Moehne and Verse Dam was use of stainless steel. This required special conditions during production and installation of the components in the plant and on the construction site.
The underwater rehabilitation work at Ennepe Dam took 5 years. The estimated cost of the entire bottom outlet rehabilitation project was 4 Mio. EURO. The cost of supply for the stainless steel was between 11 and 14 € per kilogram. The additional cost for the installation of the pipework was between 20 and 30 € per kilogram of stainless steel.

UNDERWATER REHABILITATION PROJECTS

Mornos Dam, Greece

Introduction

The engineers of the Ruhr River Association have been involved in a feasibility study for the rehabilitation of the bottom outlet of Mornos Dam, Greece. With a storage capacity of 780 million m³, a height of 126 m and a crest length of about 800 m Mornos Dam is one of the largest earth dams in Europe and very important for the water supply of Athens. Due to the dimensions of the upstream reach there is no access to the bottom outlet gate with conventional diving techniques. In the following some options for the inspection and rehabilitation, as well as some ROV–techniques, methods of saturated diving and pipe freezing are described.

Description of the Bottom Outlet and the Transfer Device

The bottom outlet of Mornos Dam has a capacity of 400 m³/s. The horizontal reach of the intake tunnel has a length of more than 450 m and a diameter of almost 10 m. It narrows to a square profile of about 3 x 3 m. The bottom outlet of Mornos Dam is equipped with two roller gates.

Right after the commissioning of the Mornos Dam it became evident, that the water losses of the upstream bottom outlet gate (considered as emergency gate) amounted up to about 0.5 m³/s. A so-called transfer device was built in order to make the upstream gate of Mornos Dam revisable. The basic idea of the use of the transfer device (Figure 4) was to pull the upstream valve under balanced pressure into the top of this pressure chamber, in order to be able to operate with the top of the transfer device separately from the water pressure inside the penstock.

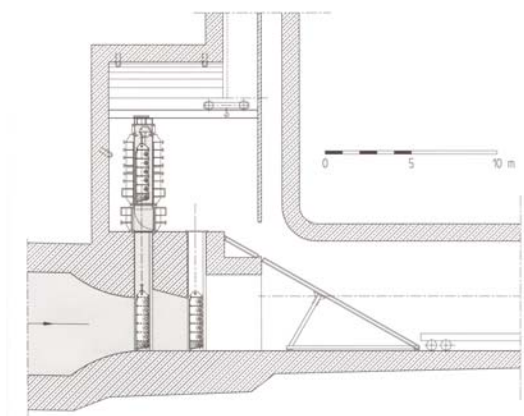

Figure 4. Use of transfer device inside the gate chamber of Mornos Dam

The use of the transfer device is a very complex and difficult operation. A failure has to be avoided. Therefore the transfer device has to go through a process of structural calculations and proofs.

The Use of Underwater Technology - Access with Divers from Upstream
At water depths of more than 60 m conventional diving reaches its technical and economical limits. The maximum water level of Mornos Reservoir requires the technique of saturated diving. The divers stay inside a system of chambers (so-called “habitat”) for several weeks and remain on “ground depth”. The divers are brought down to their working depth with a mobile diving bell. The supply of the diver out of the bell with breathing gas and heating water is maintained by means of an umbilical. According to the relevant safety regulations the length of the umbilical is limited to 30 m.
Therefore the use of this diving technique at Mornos Dam has to be ruled out due to the very long distance between intake and closure gate. For the same reason autonomous diving techniques is impossible too.

Access with an ROV (Remotely Operated Vehicle) from Upstream
During the last years the so-called ROV´s became widely used in underwater technology. The water depth of 120 m is no problem for a modern ROV. The main difficulty for an ROV at Mornos Dam is the enormous horizontal distance. A very powerful ROV has to be used, which is capable of driving 450 m from the intake tower to the upstream gate.

Access to the Bottom Outlet with an ROV from Downstream
It was examined, if the use of an ROV from downstream offers technical and economical advantages. By using the two gates as a lock it is possible to enter the bottom outlet with an ROV (Figure 5). This procedure requires the penetration of the umbilical through the downstream steel plate, which is no major problem. Then the upstream gate can be raised that much, that the ROV can pass safely underneath.

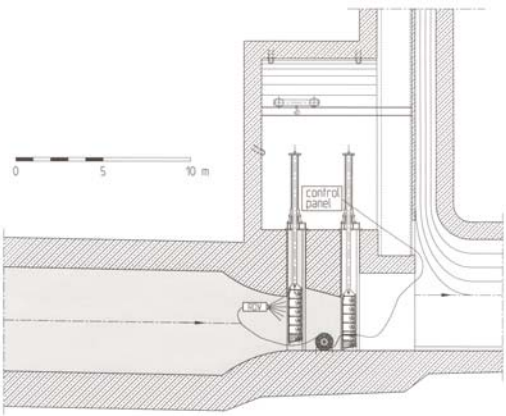

Figure 5. Inspection of Bottom Outlet with ROV from Downstream

Access with Divers from Downstream at full Storage Level

A technique is presented below, which allows diving activities at full reservoir level on the upstream side of the bottom outlet gate. This requires the use of the method of saturated diving. By installing a specific flange in the downstream gate a pressure chamber can be connected to the bottom outlet gate.

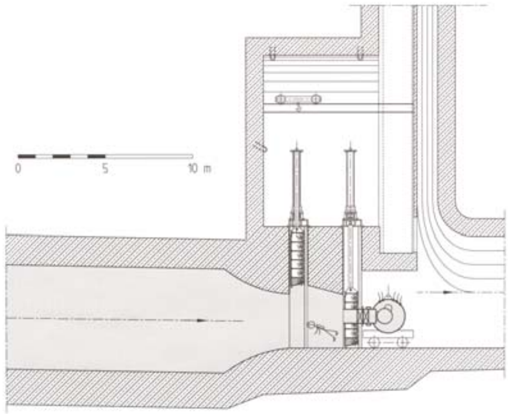

Figure 6. Access with Divers from Downstream

Access with Divers from Downstream at reduced Storage Level

A method of access with divers (Figure 6) at full storage level is described above. At a draw-down of the reservoir to about 80 - 90 m dives with partial saturation get applicable.

At these depths breathing gas mixtures like TRIMIX would be used, but there are still enormous decompression times from a dive with a ground time of 30 minutes:

water depth [m]	decompression time [min]
80 m	175 min
90 m	225 min
100 m	260 min

Use of non-conventional techniques

The basic requirement for the access to the bottom outlet under atmospheric conditions is an emergency gate, which has to be positioned in front of the intake trumpet upstream of the closure gate. Due to the conditions at Mornos Dam there is **no** way to install a conventional temporary emergency gate. Therefore in the following an approach is described, which possibly facilitates the access to the bottom outlet under atmospheric conditions with a non-conventional method.

Rehabilitation of the Bottom Outlet by means of Freezing

In the last 20 years the methods of freezing became widely used in the fields of geotechnical- and offshore-engineering. In the field of pipeline engineering the so-called pipe-freezing - the placing of ice plugs in pressure conduits for inspection and repair purposes - became a common method in the last years. By means of a so-called jacket the coolant is brought onto the pipe from outside. By freezing both the pipe wall and the medium inside an ice-plug is produced, which is connected tightly to the pipe wall.

The installation of an ice-plug of this size inside a bottom outlet has never been done before. Therefore material testing has to be conducted. The creep of ice-samples of this size has to be examined. For the production of an ice-plug of this size the problem of convection has to be solved

Rehabilitation of the Bottom Outlets of Early Embankment Dams

The experiences gained during rehabilitation of the Ruhr River Association's dams respectively their bottom outlets could be applied not only to a very large hydraulic structure like Mornos Dam. Also very early embankment dams with Puddle Clay Core could be refurbished, applying the same or adapted underwater rehabilitation techniques. A typical example is Lower Vartry Dam (Figure 7), near Roundwood, County Wicklow, Ireland.

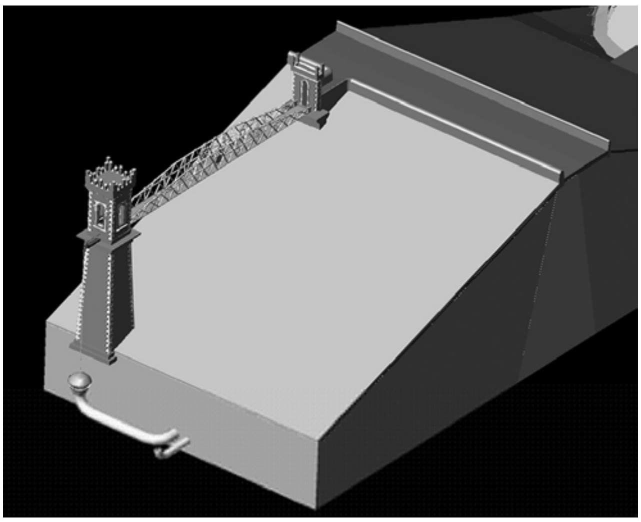

Figure 7. Schematic View of Upstream Side of Lower Vartry Dam

As a follow-up of the 12th Conference of the British Dam Society, *Reservoirs in a Changing World*, held at Trinity College, Dublin, September 2002 some aspects of the rehabilitation of the bottom outlet of Lower Vartry Dam have been discussed. It can be stated, that the basic rehabilitation techniques, which have already proven their feasibility at the Moehne, Verse and Ennepe Dam can be applied at Lower Vartry Dam as well, which might be (in brief):

- removal of sediment in the inner culvert and replacing it with concrete
- installation of guard valves inside the outer culvert behind stop-wall
- installation of new pipework and regulating valves in outer culvert
- use of the existing ball plug as a temporary emergency gate
- use of an additional valve at the intake as permanent additional guard valve respectively emergency gate.

Experiences of the Ruhr River Association show, that this work can be done at full reservoir level under full operation of Vartry Waterworks. Techniques like pipe-freezing to stop the flow during construction can not be used at Lower Vartry , since the pipes are made of cast iron, which has a tendency to fracture at extremely cold temperatures.

CONCLUSION

A number of successful underwater rehabilitation projects carried out by the Ruhr River Association has proven, that down to water depths of 50 – 60 m the rehabilitation techniques have become state of the art. Nevertheless, a number of fatal accidents in professional diving during the last years indicate, that safe working conditions should not be taken for granted. The dam owners have to insist and enforce, that the diving contractors provide the best possible safety features and working conditions. Otherwise fatal accidents are almost inescapable. Well equipped diving platforms with decompression chambers should be a must on every underwater rehabilitation site. It has also be stated, that the inspection and rehabilitation of very large hydraulic structures with water depths of more than 60 – 80 m and extreme dimensions especially at the upstream intake are still a challenge. The basic layout of many of these structures turns out to be rather disadvantageous for inspection and rehabilitation. Apparently minor design deficiencies can prove as extremely costly with regard to rehabilitation. The design of new structures should focus on this problem much more.

Some of the sophisticated inspection and rehabilitation techniques described in this paper (like ROV and saturated diving) can be considered as state of the art, but in combination with unusual features of the hydraulic structures (like extreme dimensions) there is still a lot of practical knowledge to be made. Techniques like pipe-freezing seem to be not ready for the practical use in large hydraulic structures yet.

Therefore the international exchange of experiences in the field of inspection and rehabilitation of large hydraulic structures is vital for the future of our water infrastructure.

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