THE REHABILITATION OF DAMS AND RESERVOIRS

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Contents

1. Introduction

There are more than 36 000 dams in the world. In 1950 there were 20 000. That means there are now at least 20 000 dams in the world more than 50 years old. This is the challenge we face in dealing with rehabilitation. Many of these dams were built under difficult circumstances with inadequate resources, the population in desperate need of drinking water, hydro electric power, or flood relief.

The world is becoming more litigious and many countries regulate dam design, construction and operation. There is therefore often a need to rehabilitate a dam following a review of the design to check that it complies with current standards.

The purpose of this article is to present an overview of the state of the art in dam rehabilitation, to highlight the major innovations and to provide sufficient references for the non-specialist to pursue areas of particular interest. Case histories are used to illustrate the methods.

2. Management of Rehabilitation

2.1 Management of Design

Good practice in terms of monitoring the behaviour of a dam should comprise the following as a minimum:

- Sufficient monitoring equipment in good order to be provided to allow a basic understanding of the behaviour of the dam.
- Measurement data to be regularly evaluated.
- The dam should be inspected regularly and independent advice should be called for when unusual behaviour is noted.

The first step in rehabilitation is to develop an investigation programme to define the extent of rehabilitation, and the methods to be used. Operating experience should be established through structured questioning of operating personnel and reference to published work. Hydrological studies may suggest an increase in spillway capacity, power studies may recommend more hydroelectric capacity or irrigation and water supply and these possibilities should be included in the programme. It is costly to take important hydraulic structure out of operation. There may be an annual window when investigations can be made, and failing to use the window can delay the work by a year. The owner and the financing agency may have to agree urgently on the most practicable and expeditious way forward. They may agree to single source or price enquiry contracting for specific services.

Often the problems are complex, emphasising the need for lateral thinking when devising solutions, and the foresight to know what data will be required and when. Senior experienced personnel are required. A brainstorm approach may be appropriate. A site inspection is essential.

Having examined the available data and understood the problems, the engineer undertakes a feasibility study to identify the possible solutions to each of the problems. At this level of study the engineer identifies the options and examines them from technical and economic points of view. Comparison is usually on the basis of benefit/cost ratios. The bases of costs and benefits are kept consistent from one option to another so that meaningful comparisons between them can be made quickly and at low cost. In this way he identifies and excludes options that do nor merit costly data collection.

Integral to the feasibility study is arranging the financing of the rehabilitation work. The source of funding depends on several factors. If there are definable and reliable income stream for the rehabilitated project it may be possible to arrange private funding in which an investor takes an equity share in the project for an agreed period. Where the income stream is neither well-defined nor politically reliable, grants or loans from a funding agency become relatively more likely. The financial arrangements depend on how the rehabilitation project may be structured into fundable contracts without comprising the progress of the works.

2.2. Management of Construction

Surprises are endemic in rehabilitation. A good contract for rehabilitation work therefore requires the work to be defined accurately. The selected form of contract must be equitable for both parties, minimizing the points of conflict, and permitting the quick and fair agreement of additional work. Alternative forms of contract for rehabilitation work include: the *bill-of-quantities* format, *cost-plus*, *target cost*, and *design and construct*.

Careful structuring of pre-qualification documentation ensures that the owner, his engineer, and the funding agency receive appropriate information to judge which contracting companies are to be included in the tendering list. Joint ventures between local and off-shore contractors are favoured for two principal reasons. The local contractor brings intimate knowledge of the local business environment and government procedures while the international company brings project management and technical skills. The form of joint venture can be specified in the contract.

The construction manager needs regular submissions of supporting data from the contractor and needs to generate significant records himself. Experience is needed to anticipate problems before they arise and to arrange for the necessary data to be collected in good time. The site supervisory team must be organized so that every critical piece of permanent construction is witnessed and monitored. Each position in the team carries well-defined responsibilities. The team must always be led by a person with sound technical skills and contracts administration experience.

2.3. Risk Management

Dam operators increasingly carry out risk management to assist in the identification and quantification of potential threats to the works, and to manage the risk effectively. This allows better decisions to be made concerning the rehabilitation of ageing structures, taking into account both the value of the asset to the business and the safety of the public. There is often inadequate operating data available to assess failure frequency, particular for remote plants, underlining the value of experience and generalized statistical data. It emphasises too the value of a comprehensive data base of operating incidents. Whether or not they reflect well on the operating staff, they are encouraged to report then faithfully. The priority in assessing risk is to understand the consequences of a failure in terms of the business that relies on the works. The study should include assessment of the safety of the general public. Several approaches to risk analysis have been proposed to supplement the direct and effective method of inspection, analysis and reporting which suffer from the limitation that they principally identify defects that have already developed.

A technique described by Beak *et al* (1997) is known as the Failure Mode, Effect and Critically Analysis (FMECA). This is based on a British Standard (5760 part 5 1991). It involves applying simple criteria to an engineering system in order to identify the areas of greatest risk. Potential modes of failure are identified for each component of the works. For each failure mode the severity of the event is assessed, taking into account (a) the effect of failure on the operations, environment and wider community, (b) the probability of the occurrence and (c) the likelihood of the failure being detected. Each of these three circumstances is assigned a relatively coarse indicator on a rising scale, typically 1 to 5. The term *criticality* is given to the product of three indicators. The method produces a qualitative rather than a quantitative result. The actual probability of the event occurring is not calculated but the approach identifies which elements of the works pose the greatest threat and is useful in allowing effort to be concentrated on those elements.

Several approaches to a probabilistic risk analysis have been proposed. This technique has been used for a number of years by the chemical and nuclear industries. It has been argued that in both of these industries the works are largely constructed of standard components with well known reliability, whereas every dam is a prototype with the reliability of its components being less easy to define. It has also been asserted that the results obtained from studies of chemical or nuclear plants are less precise than has been assumed.

Typical of the probabilistic approach applied to dams is the procedure detailed by Bowles *et al* (1990) and Vick *et al* (1996). This involves developing all the possible failure scenarios that could develop as the result of a triggering event and developing them into an event tree. A probability of failure is then allocated to each component of each scenario. Thus the probability of each of the components of the tree occurring is assessed and the overall probability of each of the failure modes identified is calculated as the product of all the components in that branch of the tree.

This technique provides a quantitative risk of failure for every failure path identified and for each possible event. It is therefore possible to use this to justify whether to carry out works based on comparison of the calculated risk with a predetermined acceptable risk of loss of life or cost to the community or operator. It must however be borne in mind that the overall risk has been developed as a product of many components. A small error in each component may have a significant effect on the overall assessment. Calculation of accurate probabilities of failure for the various elements of the tree can be difficult and usually involves significant costs.

This technique has been further developed into the Portfolio Risk Assessment (PRA) approach by Bowles *et al* (1998). This is usually based primarily on available information, without performing extensive additional analyses or investigations; the steps are normally conducted at a reconnaissance level and make use of professional judgment which leads to an engineer certifying aspects of safety of the dam. Subsequent to the initial PRA, additional engineering studies will usually be necessary to verify the need for remedial work and to justify the extent of the work. As with the FMECA technique, this produces a qualitative rather than quantitative result.

Hoeg (1996) describes a simplified probabilistic risk analysis in the re-certification of existing rockfill dams that seeks to use the rigour of a logical approach via an event tree while making full use of the professional judgment of the engineers involved. The first step is a site inspection—a desk study is not an acceptable alternative. Next, all possible failure modes are visualized and defined. Those that lack technical credibility are eliminated. The third step is to construct an event tree that allows the interrelationships between events to be displayed. Only those events that lead to an uncontrolled release of water are developed at this stage. Each of these events is then reviewed to find those with greatest probability of occurrence, perhaps using a simple scale of likelihood from *virtually impossible* through very *unlikely, completely unknown* to *complete certainty*. The final step is to review the results from the event tree to determine the reasons for certain failure modes giving larger contributions than others.

Other methods include the production of fault trees and Hazop studies. With a fault tree the initial consideration is the failure of the element being considered and a tree is built up to establish the various means by which the failure could develop. As with the event tree the probability of each component is assessed to calculate an overall probability of failure. Hazop is a well estabilished technique used in the chemical industry and bears many similarities to the event tree process but uses standard probabilities of failure for the components used in the construction of the plant.

None of the techniques remove all risk. The aim is to reduce the risk of failure to one that is *As Low As Reasonably Practicable* (ALARP). The basis for ALARP is that risks are acceptable only if reasonably practical measures have been taken to reduce risks. This is commonly taken to mean that the risks have been reduced to the point where it is longer cost effective to reduce them further.

With all the methods of risk assessment the procedure should involve a team including engineers with experience of design, operations and maintenance and may also require advice from specialists in hydrology, geology and seismology in order to develop a comprehensive assessment. A site visit by the team to inspect all aspects of the works is essential, as are discussions with the local operators and the study of such construction drawings and operational records as can be obtained, to enable them to produce a worthwhile assessment.

3. Rehabilitation of Foundations of Concrete & Masonry Dams.

3.1. Introduction

Three important scenarios in which the foundations of masonry or concrete dams need rehabilitation are described below, together with a description of appropriate methods. Table 1 summarizes some case studies describing the methods mentioned below.

Cause of rehabilitation	Dam data					Rehabilitation
	Name	Height m	Type	Construction date	Country	
Loss of strength under repeated loading	Albigna	115	PG		Switzerland	After 20 years, permanent displacement of the foundation noted. Successfully treated by grouting the foundation rock joints.(Kovari, 1985)
Loss of strength under repeated loading	Zeuzier		VA	1957	Switzerland	After 20 years, substantial foundation movements noted. A recently constructed tunnel 400m below the dam and 1400m was responsible for draining the foundation. Successful treatment of grouting the foundation to inhibit the drainage of water (Mueller *et al*, 1985)
Erosion and solution	Lister	40	PG(M)		Germany	The hydraulic gradient from the reservoir to new drainage gallery was steep enough to erode the fillings from joints in the foundation. Successful treatment was to reduce the hydraulic gradient by flooding the drainage gallery (Rissler, 1994).
Erosion and solution	Henne		PG(M)		Germany	Soluble foundation rock became so pervious that the effective solution was to abandon the dam (Heitfeld, 1961)
Ageing grout curtain	Schlegeis	131	VA	1973	Austria	Cracked grout curtain repaired with a new 5m deep cut off wall (Floegl *et al*, 1991)
Blocked drains	Baitings	53	PG	1958	UK	Choked foundation drains replaced.

Table 1. Rehabilitation of foundations of concrete and masonry dams

3.2. Loss of Strength Under Repeated Actions

Rehabilitation may be needed when the foundations rock is damaged by alternating stresses caused by the variation in hydraulic gradient experienced when the water level in the reservoir changes. These variations may lead to deformation, to movements on joints and to the initiation and propagation of cracks. There may be changes in the water content and pressure within joints. The rock mass is usually strong enough to adopt a new equilibrium after several years of operation. Sometimes, however, there is permanent change that may adversely affect the seepage quantity, uplift pressure and rock strength over a long time scale so that rehabilitation is needed. Such effects are usually detected through reliable and detailed monitoring. The aim of rehabilitation is usually to strengthen the foundation by grouting, improving the drainage, or by installing an impervious apron upstream of the dam.

3.3. Erosion and Solution

The flow of water through erodible or fractured rock can lead to increasing leakage from the reservoir. Large flows may be observed when the rock itself or the joint infill is soluble, resulting in karstic caverns. Detailed investigations of the foundation rock mass at the design stage is the best way of avoiding this problem. Monitoring the volume and pressure of the seepage through the foundation will be helpful in giving warning of this condition. A useful correlation of seepage quantity and pressure shows that when both are increasing, urgent rehabilitation may be necessary. When both are reducing no action is necessary to improve the foundation drainage. Rising seepage and decreasing pressure reveals the possibility of erosion within the foundation.

The aim of rehabilitation is to reduce the seepage flow through the foundation. Improved drainage to reduce the seepage pressure of the water may also be appropriate for rehabilitation, but care is needed. The case history of Eder dam, shown on Table 3, is one in which the improvement of the drainage within the foundation caused increased seepage and consequential erosion.

3.4. Ageing Grout Curtains and Drains

Grouting is one of the most common current methods of reducing the seepage below the dam. Older dams often were not provided with a grout curtain. Although cement is the most frequently used material for grouting, other materials are used in specific circumstances where, for example, the seepage paths to be grouted are particularly fine.

Drainage systems are designed to intercept and reduce the pressure of the water seeping below the dam. They include galleries, tunnels and bore holes. Both grouting and drainage are among the most useful measures for rehabilitating the foundations of ageing dams. When these elements deteriorate, owing to poor maintenance, or to chemical or physical attack, seepage may increase in quantity or it may begin to carry sediment. There may develop unusual readings of piezometric pressure. Rehabilitation usually consists of reconstructing the ageing component whether it is the grout curtain or a drainage system.

4. Rehabilitation of Concrete and Masonry Dams

4.1. Introduction

The four most common scenarios triggering the need for rehabilitation of the body of concrete and masonry dams are described below. This is followed by a brief account of rehabilitation in particular circumstances: at structural joints, in pre-stressed structures, and where the rehabilitation is required to improve the static stability of the dam. Table 2 summarizes a selection of case histories.

Cause of Rehabilitation	Dam data					Rehabilitation
	Name	Height m	Type	Construction data	Country	
Chemical reaction resulting is swelling	Chambon	90	PG	1934	France	Slots cut in the concrete to relieve the stresses. Expected to be in repeated in 5 to 10 (Taddei et al, 1996).
Shrinkage and creep leading to contraction	Olef		Buttress	1955	Germany	Detailed monitoring and analysis justified additional concrete and post tensioned anchors (Baecker et al, 1985)
Degradation at dam faces	La Girotte		Mult arch	1949	France	Comparison of facing repair methods show the good performance of a pvc facing (Bister et al, 1993)
Degradation at dam faces	Agger	45	PG	1928	Germany	New 120mm thick asphaltic concrete face has lasted 30 years. (Feiner et al, 1967)
Degradation at dam faces	Pracana	65	Buttress	1948	Portugal	Successful repair using pvc facing (Silva Matos et al, 1993).
Degradation at dam faces	Lost Creek	36	VA	1924	USA	Successful underwater installation of a pvc facing. (Harlan et al, 1998)
Loss of strength due to repeated actions	Zillergrundi	186	VA	1978	Austria	Locking of the joints in the dam by grouting. (Schoberl et, at 1993).
Loss of strength due to repeated actions	Ternay	41	PG	1867	France	Additional structural support through recountring.(Lino et al, 1991)
Loss of strength due to repeated actions	La Bourne	18	PG	1878	France	Increase of the overall level of compressive stress using post tensioned anchors. (Lino et al, 1991)

Table 2. Rehabilitation of concrete and masonry dams

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