THE AGING AND REHABILITATION OF APPURTENANT STRUCTURES TO DAMS AND THE AGING OF MASONRY DAMS

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Summary

The causes of deterioration are outlined, together with measures to rehabilitate appurtenant structures to dams. Causes of deterioration include aging and can be related to design or construction deficiencies, worsening with time, or to extreme service conditions including flooding and earthquakes. Local effects of deterioration can reach disastrous proportions, threatening structural integrity and the satisfactory operation of hydraulic equipment, if not attended to regularly.

Abrasion by particles of rock or sand in high-velocity flow, cavitation, and erosion of weak materials can cause progressive deterioration. Appurtenant works such as spillways, stilling basins, energy dissipaters, and outlet works are the areas most at risk. Remedial measures might not be permanently successful and repeated attention might be necessary. The use of additives and materials, such as polymers and epoxies, are often advocated to effect repairs. Obstructions can occur at outlets, leading to complications of emptying the reservoir of water or silt or to overtopping.

Masonry structures, built mainly during earlier times, are also subject to deterioration. Concrete is also vulnerable, for example, to alkali aggregate reaction. Case histories review and illustrate measures to combat deterioration. Tables list types of masonry construction and aspects of original design of masonry structures for use in rehabilitation.

1. Introduction

This article deals with some aspects of the aging and consequent rehabilitation of appurtenant works of dams. Appurtenant works include spillways and outlet works, together with their gates and associated control equipment. The final section of the paper deals with the aging of masonry dams (see *Concrete Dam Engineering; Hydraulic Control Structures*).

Of particular importance to this paper is the body of replies to ICOLD's Question 71. The General Report by Pinto will be of particular assistance to engineers tasked with managing the rehabilitation of the appurtenant works of dams. Much, but not all, of the damage to appurtenant works tends to be brought about by the effects of flowing water. Corrosive processes affect some elements (see *Corrosion Protection of Metals*).

The aspects of the aging and rehabilitation of appurtenant works to dams that do not relate to the flow of water are the same as those found in concrete and masonry dams themselves. They include problems with deteriorating foundations and the body of the structure owing to the effects of physical or chemical processes. They are not discussed further here (see *Degradation of Concrete: Alkali Aggregate Reaction; Rehabilitation of Dams and Reservoirs*).

The circumstances leading to rehabilitation will be discussed, and then selected case histories of remediation will be presented.

Knowledge of the loads imposed and the behavior of dams increases with time. This can lead us to the conclusion that a dam will not behave safely in some circumstances. The risk to society might no longer be acceptable. In these circumstances the dam or its appurtenant works could require remedial works.

The most common reason for remedial works in this context is to increase the maximum flood that can be passed safely by the spillway. However, engineers do not usually regard this as an aging process, and work relating to the increase of spillway capacity is reported elsewhere. Changed land use downstream of a dam can also require an increased level of security (see *Design of Spillways and Outlet Works for Dams*).

Aging of appurtenant works is normally detected through regular dam safety reviews. Problems can be brought into focus where similar structures have misbehaved or where the mode of operation changes. The design assumptions of each critical item should be reconfirmed regularly. Risk analyses sometimes reveal that the hazard posed by a dam is too high or that the consequences of failure have increased due to changed circumstances downstream. It is becoming increasingly common for owners to formally evaluate hazards and risk before embarking on costly rehabilitation works. This can lead to a reduction in the amount of rehabilitation required.

An account of the aging of masonry dams is included in view of the prevalence of masonry construction in the early practice of dam building. These structures still perform in a satisfactory way, although they are subject to some deterioration. Therefore, the reasons for their aging and the possible remediation techniques are included in this article.

2. The Principal Causes of Deterioration

Deterioration of appurtenant structures to dams is caused mainly by local scour, erosion by abrasion, erosion by cavitation, and by obstructions.

2.1. Local Scour

This term usually describes the effects of fast-flowing or turbulent water on natural materials including rock and soil. The energy of the flow over a spillway crest or through a bottom outlet is dissipated in the chute, culvert or tunnel, and the downstream works. The impact, turbulence, and friction of the water generate hydrodynamic forces against the faces exposed to the flow. Experience has shown that these forces are often not well understood or that their magnitude is underestimated. Hydraulic structures are sometimes underdesigned in this regard and suffer significant damage as a result.

Erosion that can in extreme circumstances lead to the undermining of a structure can be a consequence of local scour. Spillway structures on sand or soil foundations older than 25 years and with a history of frequent operation at high flows are particularly susceptible to erosion of the foundation. Scour of rock or concrete surfaces is greatly accelerated when the flowing water contains suspended sediment. Thus, for example, scour outlets and low-level outlets, where the reservoir is heavily silted, often require special treatment. Close study of the geology is essential to ensure stability where the rock foundation adjacent to the dam might be eroded.

There are at present no analytical or experimental methods for forecasting scouring phenomena definitively. Periodic visual or sounding surveys and inspections by divers are essential. These inspections are better done when the discharge or the reservoir level is low, and special arrangements might be required to facilitate them. Piezometers, devices to measure the pressure of water within the foundation, are sometimes useful in revealing the effect of the increased seepage flow where erosion has occurred.

2.5. Erosion by Abrasion

Solid particles entrained in the flowing water abrade hydraulic structures. The extent of damage is a function of velocity and turbulence in the flow and of the hardness of the abrasive material and the nature of the surface being abraded. Hydraulic-jump stilling basins and bottom outlets are particularly vulnerable to abrasion damage. Asymmetric flow produces unhelpful flow concentration in which local damage can be rapid and severe.

Sediments trapped in the reservoir are often released through scour and low-level outlets. Damage has been reported in the conduit lining, gate and valve parts, and pipes. Particularly vulnerable are outlets used for diversion during construction, for reservoir sediment release, or for outlets designed for the control of reservoir sedimentation.

Abrasion has been caused by rock drawn into hydraulic-jump stilling basins from downstream by reverse currents. Some basins tend to continue to circulate the material rather than eject or sweep it from the basin. Other sources of material include construction or maintenance debris, objects thrown by visitors, or fallen rock from side slopes. The circulation of sand and rocks is similar to the action of a ball mill, causing severe erosion of floors, side walls, floor blocks, and the energy-dissipating teeth. The depth of erosion could reach meters in a short time.

Abrasion is sometimes noted at a discharge much smaller than the design discharge, especially where a high tailwater level causes the hydraulic jump to form farther upstream than was designed. Immediately downstream of a flip bucket, in cases where the low flows are not thrown clear of the base of the terminal structure, the foundation of the structure could be eroded by the dribbling flow. The flip bucket might then be rendered unstable. Regular inspection of stilling basins and low-level outlets is the only reliable means of detecting the extent of damage. Underwater inspections might be required. Exploratory drilling can sometimes be helpful in determining the depth of abrasion.

Abrasion action causes pitting of a concrete surface, first eroding the cement paste surrounding the aggregates. Sometimes the exposed aggregates are damaged or detached from the surface. As the process develops, the concrete can be eroded down to the reinforcing steel. The process can, over time, lead to a catastrophic failure. Once damage to concrete or steel surfaces has started, the erosion accelerates with each operation of the spillway or bottom outlet unless the abrasive materials are removed.

Cavitation can also be triggered at the surface irregularities caused by abrasion. This can greatly increase the rate of destruction. On metal surfaces, the story is broadly similar: abrasive action can result in insufficient material remaining to perform the design intent. The abrasive action often causes pitting, which in high-velocity flow will result in cavitation and rapid removal of the surface.

2.5.1. Rehabilitation Options for Scour and Abrasion

Rehabilitation options for structures suffering from scouring or abrasion damage fall into three major categories: repair of the damaged surfaces, redesign to avoid the flow conditions responsible for the damage, and improved operating techniques.

Abrasion damage can be repaired and minimized by constructing flow surfaces of special concrete or resistant material such as stainless steel. Natural materials are often useful, particularly block work of good quality igneous rock. Test results show the resistance of a range of materials to attack by gravel in water. Even high-strength concrete was eroded much faster than stainless steel, and this indicates that in the most severe cases the more expensive solutions might be warranted, particularly for the repair of highly eroded areas under severe attack. Some successful approaches are outlined below.

Silica fume in conventional concrete is an effective means of improving resistance to erosion by surface abrasion. This extremely fine silica powder acts as a pozzolan, but results in a harder and stronger cementing paste in the concrete. Paste or mortar in concrete is susceptible to erosion by wear. Good quality hard aggregate will resist wear better than normal mortar. The combination of high-quality aggregate in silica fume-modified concrete results in a harder and more durable material, well suited to severe erosion environments. Regarding the performance of calcium aluminate cement and calcium aluminate aggregate, cylinder compressive strengths of 50 MPa in 24 h are possible, and the resulting material has shown in tests to be an effective repair material with good adhesion and durability under severe abrasion coupled with high water velocity.

In the design of structures to pass silt-laden or fast-flowing turbulent water, it is important to exclude the abrasive content of the flow as far as possible. This is often impracticable by the time rehabilitation is contemplated. Except for diversion flows during construction, most reservoir outlets do not routinely carry a significant amount of abrasive material in their releases. In outlets designed for diversion, it is usual to provide for full functionality after an appropriate allowance has been made for the material removed by abrasion.

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Biographical Sketch

Geoffrey Sims obtained the degrees B.Sc. (Eng.) (Hons.), Bristol University, 1962, and C.Eng. and Ph.D. (Fluid Mechanics), Cambridge University, 1968. He was made fellow of the Institution of Civil Engineers in 1988. He has more than 35 years of experience worldwide in the management and execution of large civil engineering works associated with water (design and rehabilitation of barrages, dams, pipelines, tunnels, and shafts for hydroelectric and irrigation projects). As a member of the All Reservoirs Panel, Reservoirs Act (1975), since 1989, he is involved with the inspection of dams in the UK and overseas. He is responsible for departmental management for technical and business development and budgeting. He renders specialist technical advice on risk management. Other important appointments include membership on the ICOLD Committee on Dam Aging (1986–1994), ISE Committee on Alkali Silica Reaction (1989–1992), and DTI Mission: Safety of Concrete and Masonry Dams (1993), and chairmanship of the British Dam Society (1993–1995) and the ICOLD Committee on Rehabilitation of Dams (1994–). He is author of 31 technical papers and the winner of the ICE Overseas Premium (1989) and of the Halcrow Premium (1996). His professional experience record comprises the following: Principal Consultant, Howard Humphreys and Partners Ltd. (1998–), Divisional Director, WSP International (formerly GCG, Coode Blizard) (1995–1998), Director and Chief Civil Engineer, formerly Principal Engineer, EPD Consultants, Balfour Beatty PEL; projects included major underground elements of the English Channel Tunnel (1975–1995), Project Engineer, Snowy Mountains Engineering Corporation, Australia (1970–1975), Civil Engineer, Hydro Electric Commission, Tasmania (1968–1970), and with Binnie and Partners, engaged on aspects of the Mangla Dam Project, Pakistan (1962–1964).