Dam Rehabilitation & Improvement Project

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India's Ageing Large Dams — Lessons from DRIP

Krishna Raja Sagar Dam

Construction deficiencies, earthquakes, and large floods are some of the reasons for dam deterioration, but ageing and inadequate maintenance are the main causes. Examples from the Dam Rehabilitation and Improvement Project (DRIP) are used to illustrate features of deteriorated dams and their appurtenant structures. The processes of deterioration, good design practices that would help avoid those problems, ways of detecting and monitoring the deficiencies, and methods by which the ongoing effects of ageing might be controlled and perhaps prevented are described. To reduce the risk of dam failure, regular inspections are needed to identify potential problems and take corrective actions to remedy those deficiencies before serious consequences develop.

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Introduction

Once a dam has proved itself capable of holding back a reservoir (many dam failures occur either during construction or during or shortly after reservoir filling), its structure and component parts will begin to age. The unique nature of each dam is that every structure will age at a different rate in a different way. Some dams may remain safe for a thousand years, others may start to crack and leak after less than a decade. However, when it comes to dam integrity, age matters. Ageing is accelerated by chemical runoff in the waterways, particularly in areas that have become more industrialized in recent decades.

Outdated technology is another issue. Older dams were built with the best construction and engineering standards available at that time, but much has been learnt since then about factors that can cause a dam to fail catastrophically, such as earthquakes and floods. Some older dams may not comply with current safety standards.

At Independence in 1947, there were fewer than 300 large dams in India. By 2015, there were nearly 4,900, more than half of them built between 1971 and 1989. Hundreds more are now under construction. India ranks third in the world by country in the number of large dams after China and the United States.

While some of India's large dams were built primarily for flood control, water supply, and hydroelectric power generation, the principal purpose of most Indian dams (96%) remains irrigation. In fact, large dam construction has been the main form of investment in the irrigation sector undertaken by the Indian government (Figure 1).

By the year 2020, more than 20% of all large dams in India will be at least 50 years of age. Currently, more than 80 of India's large dams are older than 115 years (see Figure 2 for a breakdown of the ages of India's large dams). All of these dams are still very

Figure 1. Tawa Dam in M.P, completed in 1974, is a 57.91-metre high composite dam that supplies irrigation water to a 246972-hectare command area.

much in use, the oldest being Thonnur Tank (24.4 metres high), located in Karnataka and dating back to the year 1000 AD.

Ageing is a major reason for deterioration of dams and their appurtenant structures. Here we take a quick look at the effects of ageing at some of the 250 large dams included in the Dam Rehabilitation and Improvement Project (DRIP), a program managed by the Central Water Commission (CWC) to facilitate their reconditioning and structural upgrading, and to assist in developing institutional capacities for their safe operation. The Central Dam Safety Organisation (CDSO) of CWC is coordinating the project with financial assistance from the World Bank.

Large Dams in India

According to the CWC, a large dam is one that is

i. above 15 metres in height, measured from the lowest portion of the general foundation area to the crest; or
ii. between 10 metres to 15 metres in height and satisfies at least one of the following criteria, namely:

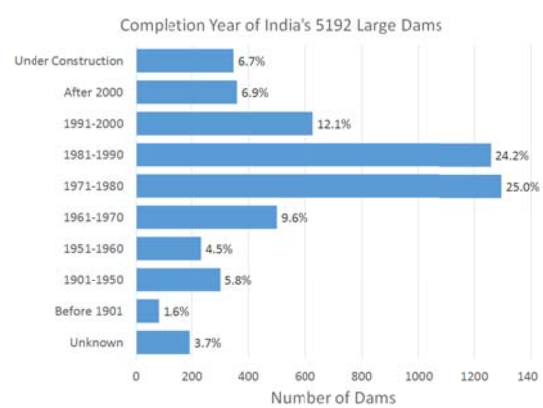

Figure 2. Breakdown of completion year of India's large dams

a. the length of crest is not less than 500 metres; or
b. the capacity of the reservoir formed by the dam is not less than one million cubic metres; or
c. the maximum flood discharge dealt with by the dam is not less than 2,000 cubic metres per second; or
d. the dam has especially difficult foundation problems; or
e. the dam is of unusual design.

Most of the large dams in India are usually earth-fill or rock-fill embankment dams, or composite dams, which are a combination of concrete or masonry gravity structures flanked by earthen embankments. These dams impound water so as to form a reservoir upstream, and a system of spillways and gates for bypassing excess water to the river and to channel water to a network of canals feeding irrigated regions downstream. The upstream areas that feed the dam and those submerged by its reservoir make up its catchment area, while the downstream areas fed by its irrigation canals make up its command area.

While dams have multiple benefits (balanced against financial and environmental costs), they can also present a risk to public safety and economic infrastructure because of the possibility of a dam failure leading to disastrous flooding, and also because of the sudden release of enormous quantities of water during extreme weather conditions to guard against overtopping and potential failure. Although failures are infrequent, the age of a dam, construction deficiencies, inadequate maintenance, and seismic or weather events contribute to the possibility of their occurrence. To reduce the risk, regular inspections are needed to identify potential problems. Corrective actions can then be taken to remedy those deficiencies before serious consequences develop.

Ageing and Degradation of Dams

As large dams age, they are likely to acquire a variety of deficiencies gradually. For example, a dam's foundation can show signs of seepage, cracking, and movement. To prevent failure or faulty operation, these deficiencies need to be identified and corrected.

Degradation of a dam is the result of time-related changes in the properties of the materials of which the structure and its foundation are composed that result in a loss of strength or structural integrity. The effects of ageing, which reveal themselves in a variety of ways, are of concern to persons involved in the dam's design, construction, operation, and maintenance. These concerns extend throughout the life of the dam.

State-of-the-art design practices can mitigate the effects of ageing. Attentiveness during construction will help avoid or delay hazardous conditions that might develop as a dam ages. Nonetheless, careful monitoring of the conditions at a dam throughout its life will be needed to identify the occurrence of ageing processes that could have undesirable impacts on dam safety.

Understanding Dam Ageing

The International Commission on Large Dams (ICOLD), Committee on Dam Ageing, studied the various ageing phenomena of concrete and masonry dams, earthen embankment dams, and their appurtenant works and prepared a report of their findings — ICOLD Bulletin No. 93. The Committee identified features of deteriorated structures, the processes of deterioration, good design practices, surveillance, detection, and rehabilitation. Methods by which the deterioration may be controlled and perhaps prevented were also identified.

To understand ageing, one needs to establish the relationship between cause and effect leading to the degradation in structural properties of a dam and its foundation. These processes are referred to as scenarios. The causes impact on the dam and/or foundation and may affect the material's structural properties. The consequences of deterioration may only become apparent after many years of operation.

Detection and Measurement of Ageing

Detection and measurement are the basis for control of ageing scenarios. Up-to-date knowledge of the dam condition is required so that anomalous behavior is detected in sufficient time to allow appropriate intervention to correct the situation and avoid severe consequences. Direct evaluation of ageing is possible by monitoring changes in structural properties. Indirect evaluations are made by monitoring the effects and consequences of changes and the actions causing them.

It is important to establish and maintain a strong data base to assess the impact of ageing scenarios on dam safety. Dam owners and engineers have access to a variety of advanced analytical tools for assessing the safety of a dam. When using these tools, it is important to remember that a mathematical tool is only as good as the data that support it. Each dam site and its environment is unique, with different characteristics governing performance. Sensible interpretation of specific site conditions and their effect on dam safety is needed.

Ageing of Concrete and Masonry Dams

Major ageing scenarios for concrete and masonry dams, their detection and monitoring, and ways to mitigate their effects are described briefly in this section. Foundation and dam body ageing scenarios are treated separately.

A gravity dam is one constructed from concrete or stone masonry and designed to hold back water primarily by utilizing the weight of the material alone to resist the horizontal pressure of water pushing against it. Gravity dams are designed so that each section of the dam is stable, independent of any other dam section.

Foundation Ageing Scenarios

Foundation scenarios are particularly relevant when the dam is underlain by very weak rock or deformable soil.

Loss of Strength

Loss of strength of the rock mass foundation of concrete and masonry dams has been the cause of major incidents and complete failures. The scenario may occur soon after the dam is put into operation (see the remnants of Tighra Dam in Figure 3), or it may take several years to develop.

The main causes of this ageing scenario are related to alternating stresses in the foundation that are caused by variations in hydraulic gradients produced when the reservoir water level changes. The alternating stresses lead to foundation deformations, movement of rock joints, and initiation and propagation of cracks. Soaking and drying of joint fillings may amplify the problem.

Erosion and Solution

The flow of water through a jointed rock foundation can dissolve and erode the rock itself, the joint infill, or injected grout. This in turn leads to movement of the rock mass resulting in increased stresses in the dam above. This weakening of foundations leading to erosion by seepage is often associated with alternating stresses that reduce the structural integrity of a dam.

Figure 3. Tighra Dam in Madhya Pradesh is a masonry gravity structure built in 1916 for agricultural irrigation and municipal water supply. The dam failed on the afternoon of Aug 4, 1917 during a large flood because of a weak foundation that could not resist the hydraulic pressure. The dam was repaired and is in operation today.

Distress of joint fillings, soil, and grout is detected mainly by increases in the quantity of seepage flow. Changes in the concentration of dissolved salts in the seepage water, and its comparison to salt concentration in the reservoir water, will reveal whether the foundation rock or infill material is dissolving.

Once a chemical reaction problem is detected, measures need to be taken to reduce seepage through the affected foundation zones. Consolidation and water-tightening of the foundation by means of acrylic resin have proven effective.

Grout Curtains and Drainage Systems

Grout curtains are used to reduce seepage through the foundations of dams. The foundations are usually composed of rock where seepage water flows through discontinuities. Drainage systems generally include grout curtains, galleries in the dam body, and tunnels in the rock mass. Collected drainage water is then discharged through a horizontal channel system at the dam body-foundation interface.

Grout curtains may deteriorate with age if they are inadequately designed or constructed. This scenario occurs because of 1) poor grouting techniques, 2) stress and deformation in the dam foundation, and 3) erosion or solution of grout by seepage water. Deterioration usually leads to increased seepage and larger uplift pressures, which further endangers the stability of the dam body.

Deterioration with time of drainage systems in dams and their appurtenant works is caused by 1) inadequate design, 2) use of unsuitable pipe and filter materials, 3) poor quality of construction, and 4) clogging of drain holes, pipes, and wells (Figure 4). Damage to grout curtains and drainage systems can impair significantly the safety of a dam and lead to catastrophic failure. The increased seepage can initiate piping, erode foundation material, and displace spillway slabs by frost heave in cold climates.

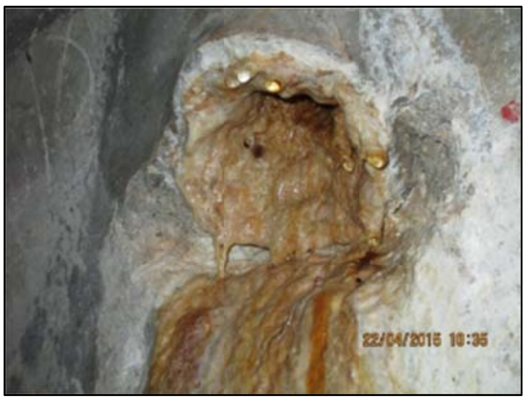

Figure 4. A clogged drain pipe at Ponmudi Dam in Kerala caused by increasing leakage and lack of maintenance. The reduction in flow through a pipe because of clogging can promote piping and lead to eventual collapse of a dam.

Dam Body Ageing Scenarios

Dam body ageing scenarios include chemical reactions resulting in swelling; shrinkage, creep, and reaction leading to a contraction; degradation caused by chemical reactions of materials; loss of strength caused by permanent and repeated action; and poor resistance to freezing and thawing.

Swelling Caused by Chemical Reactions

Concrete used in dam construction before about 1950 was generally not made to resist degradation from chemical reactions with water and aggregates. The two main causes of swelling are

- *Sulfate attack* — The chemical and physical destruction of the cement paste by aggressive, sulfate-laden waters. Degradation may be rapid because the swelling that occurs results in a significant loss of material strength.
- *Alkali-aggregate (alkali-silica) reaction (AAR or ASR)* — The chemical reaction between alkali compounds in cement with certain amorphous-silica bearing aggregates, resulting in concrete swelling by expanding silica gel.

Swelling produced by the chemical reactions varies throughout the dam body and is strongly affected by the confinement of a particular location. Cracking will occur where expansion is large (Figure 5).

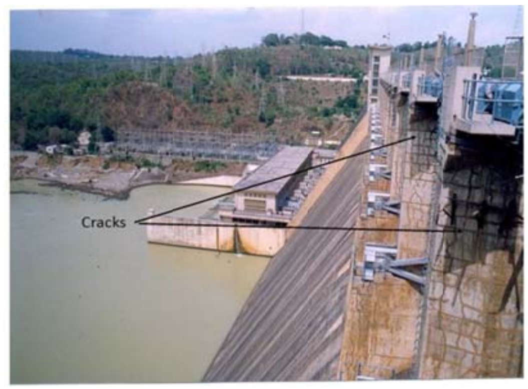

Figure 5. Large cracks have developed in Rihand Dam in Uttar Pradesh as the result of alkali-aggregate reaction.

Detection of swelling can be made by precise displacement and strain measurements. With swelling confirmed, the nature of the process, its stage and rate of development in different zones of the dam, and the confining stresses, should be determined by appropriate methods.

No efficient remedial measure against swelling caused by chemical reaction is known. Measures to mitigate the effects of swelling have included cutting slots to relieve stresses, and by reinforcement or confinement of the concrete in critical zones.

Shrinkage, Creep, and Reaction Leading to a Contraction

Concrete contracts after initial placement as curing temperatures gradually decline. This contraction may continue for decades. However, the effects of contraction are much more pronounced in thin arch and buttress dams than in massive gravity dams because the former dam types rely on large compressive stresses for stability. Reduction of these stresses by a significant amount of shrinkage can result in substantial displacement from settlement, downstream tilting, reduced stresses in the foundation leading to increased seepage through rock joints, and possible catastrophic failure. Buttress and arch dams also tend to crack in highly compressed zones as tension is reduced.

In arch dams, settlement of the crest and tilting are identified by precise long-term survey measurements and plumb lines, and by increased leakage through the foundation. Visual inspection will detect cracks.

Simple remedial measures include additional foundation treatment and re-grouting the vertical contraction joints when the dam is in a contracted state to cause it to move upstream as it expands.

Degradation Caused by Chemical and Physical Interaction of Material with the Environment

Degradation of the mechanical and hydraulic properties of concrete and masonry dams may be caused by chemical reaction of the materials used to construct the dams and external agents from the environment, specifically from reservoir and underground water, air, and temperature. There are three major parameters that govern the extent of degradation in this scenario: 1) the permeability of the dam material that controls the volume of water and gas flowing through it, 2) the pore fluids that may react aggressively with concrete and mortar constituents, and 3) temperature variation that cause cracking and the opening of joints, factors that influence the permeability of the structure. The effects of ageing from these factors are more pronounced in structures that have been built with materials of low quality, in severe climates, or in areas with chemically aggressive water (Figure 6).

Figure 6. A flooded gallery and leachate stains at Karanja Dam in Karnataka. The presence of leachate indicates chemical reactions between reservoir water and dam body materials.

The main phenomena controlling this scenario are 1) percolation through the dam of water and gas carrying aggressive chemical agents, 2) the action of aggressive water on concrete and mortar, and 3) cracking caused by rapid external temperature variations. Another serious concern pertinent to the masonry dams is the growth of excessive vegetation over dam slopes, leading to opening of joints with consequential porosity and weakening of material strength in the dam body (Figure 7).

Figure 7. Masonry gravity dams are subject to leakage caused by failed mortar and construction joints, and by the growth of plant roots that create paths along which water can flow easily, such as at Chandpatha Dam in Madhya Pradesh. Large seepage flows can remove internal material, resulting in catastrophic failure.

Visual inspection, water flow measurements, and coring to obtain concrete samples for laboratory testing are the most common ways of detecting the adverse chemical reactions of materials. Chemical analysis of water, water absorption tests of materials, and cement grouting tests in holes drilled in the dam body are also useful means of detection.

Remedial measures for this scenario attempt to restore the water-tightness of the dam by modifications to its upstream face. Methods currently in use include 1) grouting of the upstream shell; 2) use of barrier coatings such as bitumen, mastic asphalt, resins, and reinforced gunite; 3) concrete or metal facings anchored to the dam body; and 4) installation of PVC membranes on the upstream face. Local patching is also applied where cracking has been caused by cyclical temperature variations. Regular measures for weed removal from the slopes of masonry dams are also required, else application of suitable chemicals prohibiting plant growth shall be considered.

Loss of Strength from Permanent and Repeated Stresses

Some concrete dams are unable to withstand the stresses that occur under normal operating conditions, which are caused mainly by water and temperature. These stresses can be divided into a permanent component that remains constant or varies slowly with time, and a component that is approximately cyclical. Stresses form hydraulic forces, caused by the filling and operation of the reservoir, are the most significant for massive structures such as gravity dams. Thermal stresses may be more dominant in thin structures such as arch and buttress dams.

Temperature influences the behavior of a dam throughout its life owing to the thermal properties of the materials and construction techniques as well as to external temperature variations. Structures that exhibit this ageing scenario are not able to support the permanent and repeated forces under normal operating conditions. The weakness of these structures is usually shown by the growth of existing cracks, initiation of new ones, and the increase in amplitude of the permanent or repeated components of the movements of existing cracks (Figure 8).

Figure 8. Cracking caused by repeated thermal stresses in the gallery of Konar Dam, a composite concrete-gravity/earthen-embankment dam located in in Jharkhand.

Surface cracking of concrete caused by repeated stresses may begin during construction and continue over time. Influence of the cracks on dam behavior may only become significant after many years. The rate of development of such cracking often slows with time. Nonetheless, a pessimistic approach to remediation is justified because of the possibility of stress concentrations developing beyond safe limits thereby creating a major instability.

To evaluate the safety and performance of cracked dams the geometry of the cracks needs to be understood, particularly their extent, depth, and continuity. The behavior of the structure then needs to be analyzed for both normal and extreme conditions. Some cracks may give rise to leakage which could lead to chemical deterioration.

Low Resistance to Freezing and Thawing

Concrete and masonry dams exposed to water in cold climates may be damaged because of their low resistance to repeated freezing and thawing. Although this type of damage is mainly restricted to exposed surfaces, the properties of materials together with the degree of temperature variation and exposure will determine the extent of degradation. However, few large dams in India are subjected to cyclic freezing and thawing.

The behavior of concrete during freezing depends primarily on the pore structure of the cement paste and aggregates; that is, the type, size, and distribution of the pores. The pore structure controls water absorption, permeability, and thermal and mechanical properties of the materials.

Frost damage to the mortar of masonry-faced dams may cause stones to loosen and fall. The damage may extend deep into the structure as the mortar is very seldom resistant to freezing.

Damage to concrete dams subjected to frost can be prevented by using high quality materials and with thermal protection achieved by covering with granular materials on both the upstream and downstream sides, by constructing insulation walls, or by the addition of heating systems on the dam faces.

Visual inspection is the most common way of detecting areas that have been damaged by freezing and thawing. The boundary between damaged and sound zones is usually clear and can be determined by hammering. Damage will extend deeper into structures if they have been built with poor quality concrete or masonry.

The most common repair method for concrete dams is construction of a new facing. The damaged concrete is removed and the new facing is made of sprayed or cast frost-resistant concrete. Steel linings and UV-resistant, non-shrinking cementitious coatings have also been used.

Deterioration of Contraction and Lift Joints

It is good practice to provide contraction joints in gravity dams to absorb the effects of shrinkage and movement. They are usually spaced about 15 m apart, experience having shown that cracks are likely to develop in monoliths much wider than this. Lift joints are the horizontal joints between successive lifts or layers of concrete.

Contraction joints are provided with waterproofing systems to limit leakage. Ageing of the water-stops occurs often hot climates because of exposure and in cold climates because of freezing and thawing, and also from abrasion by ice. Degradation of the waterproofing system allows seepage through the dam, raising the possibility of increased uplift pressure and chemical attack on material in the dam body (Figure 9).

Figure 9. Leakage at contraction joints are typical in most masonry dams indicating failed or defective waterstops, such as shown here in the gallery of Upper Bhavani Dam in Tamil Nadu

Deterioration of structural joints is normally detected by visual inspection that identifies wet zones, cracking, and active leakage (Figure 10), or by seepage measurements that reveal continually increasing flow rates. Remedial measures include reconstruction of the waterproofing system, and packing of the joints with appropriate material, or the addition of a reinforced concrete shield.

Degradation of Upstream Facings

Membranes placed on the upstream dam face provide waterproofing and protection. They were used often on concrete dams and particularly on masonry dams in the first half of the twentieth century.

Figure 10. Leakage downstream of vertical lift gate coming from a deteriorated horizontal lift joint at Ichari Dam in Uttarakhand.

Thin concrete facings or sprayed reinforced mortar facings applied to gravity masonry dams are susceptible to alternate hot and cold weather conditions and to abrasion from ice. In cold climates these facings have been found to remain effective for about 15 to 20 years. In warmer regions they have been proved satisfactory for slightly longer periods when applied to concrete dams.

Typical deterioration of concrete and sprayed mortar facings appears as hairline cracking and detachment of sprayed mortar. Cracking results from shrinkage of the mortar and from large daily temperature variations. Cracking and detachment of mortar are common where the face is subjected to frequent fluctuations in the reservoir water level.

Squared stone pitching with filled joints is a facing made of a layer of hard stones 0.4 m to 0.6 m thick, squared by hand and fixed to the underlying face by using cement mortar. The joints between the stones are sealed by means of troweled mortar. These facings have been found to be effective on gravity and arch dams in cold climates where they are resistance to frost action and abrasion by ice. However, they are less effective as watertight barriers because the mortar filling the joints between stones is gradually damaged by cycles of wetting-drying and freezing-thawing, and by large daily temperature variations.

Ageing of Earth-fill and Rock-fill Dams

Major ageing scenarios for earth-fill and rock-fill dams, their detection and monitoring, and ways to mitigate their effects are described briefly in this section. Foundation and embankment ageing scenarios are treated separately.

Foundation Ageing Scenarios

Foundation ageing leads to significant deterioration particularly when the dam is underlain by very weak rock or deformable soil. These scenarios include deformation, loss of strength, change in state of stress, internal erosion, and foundation degradation.

Deformation

Where the foundation consists of very weak rock or deformable soil, the material is usually removed or measures taken to improve the material left in place. If not excavated properly, deformations caused by consolidation of the soil or weak rock may occur unevenly, resulting in differential settlements, which can induce fissuring of the dam body. In dry climates low density soils decrease in volume (collapse) when they become wetted, which also can induce fissuring. The fissures may be a source of piping.

Detrimental effects can be avoided by constructing zones of granular self-healing material to mitigate effects of fissures and provide drainage. Foundation settlement may be monitored with instruments installed during construction. Fissuring may be counteracted by intersecting the fissure system with a cutoff wall.

Loss of Strength, Uplift Pressure Increase, and Change in State of Stress

Loss of material strength generally occurs in clay soils because of saturation and excessive strain. More plastic clays with high dry strength will experience strength loss upon saturation. When clay soils are strained past their peak strength, they experience a significant loss of strength.

Uplift pressure builds up where the steady state seepage is obstructed or where a sudden excess in seepage cannot be accommodated. In rock with erodible or soluble joint infilling under reservoir pressure, water penetrates the joints and progressively builds up the uplift pressure. Water seeping under the dam may move fines which may progressively clog the drain filter or drain openings, resulting in pressure build up at the downstream toe. Water seeping through poorly graded material may move material (internal erosion or piping) leading to subsidence or sinkholes.

Embankments constructed in a narrow valley affected by cross valley arching may experience a decrease in vertical loading on the foundation leading to hydraulic fracturing and eventual piping of foundation material. Cyclic change of stress in the bottom of large seasonal reservoirs induces alternating shear stresses which can lead to a progressive opening of joints. When dams are founded on alluvium, lowering of the downstream water table will increase the effective stress in the soil and may lead to settlement.

Internal erosion

Erosion processes may only be observed a long time after the first filling of the reservoir, even though they frequently can be related to inadequate design or construction procedures. Internal erosion is the most common ageing scenario for the foundation of earth-fill and rock-fill dams and may form in the following ways:

- Through rock joints that are opened by being disturbed during construction and by filling of the reservoir, allowing seepage to begin through the joint network.
- From increased seepage caused by ageing of the grout curtain resulting from dissolution of the cement, dissolution of gypsum or other minerals, or by internal instability of the foundation material.

Increased seepage flow rates may reach values high enough to cause erosion, which in turn accelerates seepage and failure.

Internal erosion is usually detected by periodic visual inspection and by measuring of seepage flow. Standpipes or piezometers can be used to measure uplift pressure and evaluate embankment stability.

Remedial measures used to control internal erosion of embankment dam foundations include grouting, provision of toe drains or other filter drainage systems, relief wells, stabilizing berms along the downstream toe, upstream impermeable blankets, cutoff walls that increase seepage paths, and drainage collection tunnels.

Foundation degradation

Degradation of foundation materials implies that a change occurs in their characteristics or properties resulting in loss of strength or an increase in permeability. Materials may degrade by slaking, dispersion, solutioning, and by thermal and chemical processes. Seepage water influences these processes, which take place after first filling or develop slowly over time.

Deciding on remedial measures requires a clear understanding of the physical and chemical conditions within the foundation. A properly planned water sampling program, accurate on-site measurements, and analysis of chemical equilibrium and mass balance can provide insights to the processes that control foundation seepage chemistry.

Embankment Ageing Scenarios

Embankment ageing scenarios include deformation, loss of strength, pore pressure increase, internal erosion, and degradation of the embankment by seepage.

Deformation

The long term process of consolidation of the embankment material, after construction completion and during first filling, is the main cause of continuing deformations of the embankment. The consolidation process may be influenced by environmental (temperature, precipitation, earthquake, blasting, dam crest traffic) and operational factors (water level fluctuations). Deformation depends upon mineral type, shape, hardness, grain size distribution, and moisture and density of the compacted material.

Embankment consolidation may lead to the following complications:

- Differential deformation of adjacent sections of embankment, which may cause fissures leading to internal erosion.
- Settlement at the contact with a concrete structure initiating cracks, leaks and erosion.
- Loss of reservoir freeboard.

Long-term deformation of an embankment can be recognized by precise measurement of vertical and horizontal displacement carried out routinely. Deformations can be prevented by placing and compacting fill material properly during initial construction. Remedial measures might require complete reconstruction of sections embankment sections.

Loss of Strength

Loss of embankment strength usually results in instability of slopes and deformation. Reduction in strength of the embankment materials is associated with the following:

- Wetting of poorly compacted embankment soil. Compaction without sufficient reduction of the void volume will allow considerable particle reorientation to occur. If a large section of embankment is affected, significant settlement will occur. If occasional layers or lenses are affected, differential settlement will take place leading to cracking, piping and areas of high pore pressure.
- Some soils experience a large reduction in cohesive strength when wetted. Reservoir seepage, abutment groundwater, and rainfall may reduce embankment stability.
- Loss of embankment strength may also be caused by a change in the state of stress. Embankment heightening may stress the existing material beyond its peak strength and a lower residual strength is reached. Cycles of drying and wetting of highly plastic clays may result in slope instability, particularly shallow downstream slips. As the clay dries, capillary stresses lead to cracking by tension. When water is again available to the crack, material sloughs off into the crack and there is a loss of strength in the swelling clay at the crack face. A progression of these events would reduce the effective dam width and promote other scenarios (Figure 11).

Figure 11. Differential settlement of impervious shoulder resulting in longitudinal crack forming at the dam top above the clay core as seen inside the trench; Upper Tiruppur Dam, Tamilnadu.

Periodic visual inspections of the dam and displacement measurements will detect embankment deformations. A well compacted embankment is the primary defense.

Pore Pressure Increase

Long term pore pressure increase, pressure greater than estimated from normal permeability of the compacted soil, is generally associated with progressive opening of transverse cracks in the core or through the whole fill.

Cracking may be caused by differential foundation settlement, differential embankment compression, embankment arching (hydraulic fracture), contact with concrete structures, or drying out of the upper portion of the core during prolonged dry periods. Pressure increase may also be associated with dissolution of dispersive clays, a defective layer in the core, poor material placement, or low permeability downstream of the core.

Detection of the scenario is primarily by visual observation, supplemented by seepage measurements and pore pressure measurements (Figure 12). Remedial measures consist of grouting, installation of a cutoff wall, drainage improvement and replacement of damaged areas.

Figure 12. Leakage is monitored by collecting seepage water in discharge channels and measuring the flow using small weirs. At some DRIP dams measuring weirs have been damaged or removed making assessment of dam deterioration by internal erosion impossible. The measureing weir at Balimela Dam in Odisha shown in the photograph is oepn to the environment, unprotected, and vulnerable to damage.

Good design and construction practices may prevent excessive pore pressure increases by eliminating foundation overhangs, shaping the abutment and structure contact, use of ductile material in the upper part of the dam, adequate drainage downstream and careful material placement.

Internal Erosion

Internal erosion of earthen embankments may go unnoticed for a long time, but generally finds its origin in design and construction inadequacies. It may occur in soils susceptible to cracking, piping or other types of erosion. Internal erosion may occur within the embankment core or in the downstream shoulder.

Frequently internal erosion occurs at the embankment contact with the foundation. Embankment material may be transported through fissured rock or into solution cavities along with erodible rock fissure infilling. Causes on of internal erosion include embankment cracking, internal instability of earth-fill (glacial till), use of dispersive clays in embankment construction, or leaching of soluble minerals. Removed material induces settlements and local failures occur (sinkholes). If allowed to continue long enough, a breach may develop leading to catastrophic downstream flooding (Figure 13).

Figure 13. Gararda Dam in Rajasthan breached during the very first filling on Aug 15, 2010 because of internal erosion along the embankment/foundation interface.

Detection of internal erosion has relied on visual inspection, water flow measurements, pore pressure readings, and turbidity measurements. Drilling (using sonic drilling or other drilling method without drilling fluid) and geophysical investigations (temperature measurements, electrical resistivity, sonic refraction, and magnetic resonance imaging) have been carried out to determine the seepage paths and the extent of erosion.

Remediation has included grouting the piping path with cement or a cement-bentonite mixture (often with the addition of sand), installation of an impervious cutoff wall (sheet pile, diaphragm, or grouting in front of the embankment core section), construction of a toe drain, a new internal drain/filter, lime treatment of the fill, and replacement of the impermeable core section.

Degradation by Seepage

Degradation of embankment materials occurs when there is a change in their properties that results in a reduction of strength or an increase in permeability. Seepage is an important element for degradation processes, which may result in removal of erodible, soluble or dispersed material. Saturation may cause loss of shear strength.

Control of seepage with a well compacted embankment and internal filter and drain features is the best way to reduce or eliminate degradation. Some rock types, particularly shales, deteriorate when exposed to air and moisture in an unconfined condition. If shales are used in a rock-fill, they may deteriorate or weather into a soil, resulting in surface deformation or lowered shear strength of the rock-fill allowing slope instability. Control of seepage is important. Visual inspection and measurement of seepage water flows and chemical analysis of seepage water samples are used to monitor embankment behavior. Brush and trees growing on embankment slopes makes detection of seepage difficult and can promote additional leakage and initiate internal erosion along the paths of roots extending into the dam (Figure 14).

Figure 14 Large trees allowed to grow on the downstream embankment slope of Meenkara Dam in Kerala make visual detection of seepage difficult and can promote leakage along the paths of roots extending into the dam.

Surface Erosion

Surface erosion, although a very common ageing scenario, has not been an important contributor to embankment failures. Erosion on the downstream slope and crest may be caused by heavy direct rainfall or surface water runoff, brief crest overtopping, wave spray over a wave wall or wind driven wave spray. Also, regular use of downstream embankment slopes by local inhabitants and livestock create bare pathways that promote erosion Figure 15).

Figure 15. Surface erosion on downstream embankment of Balaskumpa Dam in Odisha. Note the absence of grass cover that would prevent soil erosion on the embankment slope.

Erosion on the upstream slope protected by riprap may be the result of wave action on riprap of inadequate size or without proper underlying filter material, or from breakdown of riprap by freeze-thaw displacement (Figure 16).

Figure 16. Displaced riprap caused by wave action on the upper slope of Thirumurthy Dam in Tamil Nadu.

Readily detected by routine visual inspection, repairs are generally straightforward and should be carried out in a timely manner. Downstream slope improvement includes directing crest runoff into the reservoir and collecting and diverting surface water down and away from the downstream slope. Regular visual inspections, particularly following unusual weather events, are necessary.

Vegetation on Embankments

Most dam safety engineers, including most dam safety officials, consultants, and other experts involved with dam safety, agree that when trees and woody plants are allowed to grow on earthen dams, they can hinder safety inspections, can interfere with safe operation, or can even cause dam failure (Figure 16). In the past, engineers and dam safety experts have not always been in agreement about the best way to prevent or control tree growth, remove trees, or repair safety related damages caused by trees and woody vegetation (Figure 17). However, all dam engineers agree that a healthy, dense stand of low-growing grass on earthen dams is a desirable condition and should be encouraged.

Figure 17. Woody vegetation inhibits dam safety inspection of Dhuty Weir located in Madhya Pradesh. Uprooted trees on the waterside of the dyke have over steepened the waterside slope resulting in large voids and reduced freeboard; and have reduced necessary x-section of the dyke for maintaining stability.

Ageing of Appurtenant Works

Appurtenant works are those structures associated with the operation and safety of a dam. Operational structures include powerhouses, associated hydraulic circuits, intake towers, navigation and fish locks, and hydraulic and electro-mechanical equipment. Structures designed to assure a safe dam include spillways, surface and bottom outlets, energy dissipaters (stilling basins, flip-buckets, plunge pools), and hydro-mechanical equipment

Ageing scenarios are considered only for appurtenant works adjacent to a dam, specifically spillways and their gates, energy dissipaters, intake structures and their gates, penstocks leading to powerhouses located near the dam, and powerhouses.

Ageing Scenarios Related to Water Discharge

Ageing scenarios related to water discharge from the reservoir include local scour, erosion by abrasion, erosion by cavitation and energy dissipation, obstruction by solids carried by the flow, problems with gates and other discharge equipment, and extreme flow.

Local Scour

Water impact can create large stresses in the rock or concrete of energy absorbing structures. The magnitude of these stresses are often difficult to evaluate, and experience shows that they are frequently underestimated. Poor understanding of the erosive forces associated with water impact at the foot of spillways can result in failure of structure and is an important ageing scenario to consider.

Local scour is detected by visual inspection or by underwater measurements using sonar or radar equipment. Where scour has developed over a long period of time, periodic depth sounding and underwater inspection by divers can be used to monitor it over time and identify the occurrence of critical conditions.

Remedial measures vary according to the degree of deterioration and location of the scour. In serious situations, complete and rebuilding of the spillway and its stilling basin or flip-bucket to withstand the erosive forces are carried out. For less extensive damage, solutions may be limited to reconstruction of damaged slabs or flip buckets with added reinforcement, thicker concrete, and a drainage system to relieve uplift pressure.

Erosion by Abrasion

Erosion by abrasion occurs most often when cobbles and boulders become trapped in a stilling basin at the foot of a spillway (Figure 18). The violent movement of the stones by large, turbulent flows provides a grinding action against the concrete floor and walls and can quickly erode enough concrete to require immediate repairs.

A less common occurrence of abrasion is along the downstream face of overflow sections where flow carrying a heavy silt load or detritus can cause heavy erosion, particularly at sharp changes in flow direction (Figure 19). Concentrated streams of silt-laden water can also damage the walls of concrete conduits and mechanical gates.

Figure 18. Energy dissipation erosion in overflow spillway at Maneri Dam in Uttarakhand. The spillway was eroded approximately five meters and set the stage for heavy remedial works.

Damage to appurtenant structures from erosion by abrasion can be detected in three ways: 1) By dewatering the stilling basin for visual inspection, 2) by underwater visual inspection using divers or remote-controlled cameras and 3) by echo sounding.

Figure 19. Spillway glacis beneath a radial gate at Ichari Dam in Uttarakhand has been eroded by abrasion from sediment resulting in significant leakage when the gate is fully closed.

Erosion by abrasion can be reduced by limiting the flow of coarse bed material at the entrance of spillways. Remedial measures include 1) provision of additional concrete, 2) patching of damaged surfaces with epoxy or resin mortar, and 3) application of sprayed concrete (shotcrete).

Erosion by Cavitation and Energy Dissipation

When, for any reason, the pressure at a point in water falls low enough for the water to vaporize, the vapor appears in the form of cavities or water-vapor bubbles. In a water stream, the cavities will travel with the flow until the fluid pressure rises sufficiently for the water vapor to re-condense and the cavities to collapse. Collapsing cavities along solid boundaries can create extremely large pressures which can erode the solid material.

Cavitation erosion by flowing water is appurtenant works is caused by the occurrence of low pressure zones, particularly in closed conduits and overflow spillways. The phenomena may be caused by inadequate venting of gates in closed conduits, or by spillway chute geometry that creates zones of low pressure. Erosion by cavitation often occurs downstream of gates when they are operated partly open.

The consequences of cavitation in spillway chutes take the form of erosion and uplift of chute slabs. Blocks of concrete may become detached from the chute floor if they are not properly reinforced and anchored. Undermining of the chute foundation can then take place, thus jeopardizing dam stability. Effectiveness of tunnel spillways may be impaired significantly by cavitation to erode linings and increases hydraulic resistance.

Deterioration caused by cavitation is usually detected by visual inspection, either above or below water. In some cases, cavitation damage has been discovered when gates fail to operate properly.

Remedial measures where inadequate venting is the cause include installation of adequate air vents in the outlet works, 2) changes in operating procedures to prevent the occurrence of low pressures in flows, and 3) replacement of gate controls. Spillway chutes and stilling basin baffle blocks damaged by cavitation are usually repaired by appropriate concrete patching. Dislodged chute slabs may need to be replaced entirely.

Obstructions by Solids

Solids carried by flows from the reservoir may obstruct low-level outlets or intakes, leading to severe damage and costly repairs. Logs, tree stumps, and other large floating debris that are washed into the reservoir are the primary causes of blockages. A contributing cause is the failure to operate outlet gates regularly, either for testing or reservoir flushing.

The immediate cause of the obstructions is the sudden opening of the outlet gates or valves, either to effect repairs or to pass floods. Clogging of intake structures often occurs by sudden mobilization of accumulated fine sediment (Figure 20).

Figure 20. Excessive sediment accumulation in reservoirs, particularly near the intakes of bottom outlets, such as at Maneri Dam in Uttarakhand shown here, can be mobilized quickly when gates are opened and obstruct flow through the outlet.

The main consequences of obstructions are the reduced flows though outlet works and the subsequent repairs of damaged structures. Where bottom outlets are made inoperable, an additional risk is created by potential overtopping of non-overflow sections of the dam.

Obstructions by solids are usually detected when outlet works malfunction. Water level gauges that measure the pressure difference across trash racks also provide useful warnings when the outlet structures are operating.

Remedial measures include construction of new outlet structures or intakes, replacement of damaged trashracks, and repairs to gates and valves.

Problems with Hydro-mechanical Equipment

Hydro-mechanical equipment includes 1) gates and valves which are used to discharge through water conveyance structures, along with their stationary metal parts that are embedded in concrete, 2) mechanisms for lifting and lowering the gates and valves (hoists, cranes, and hydraulic devices, and 3) service bridges upon which are installed the stationary mechanisms for lifting gates and values, or along which cranes operate.

Appurtenant structures may be damaged as a result of malfunctioning hydro-mechanical equipment. These incidents may be related to deficiencies in either the original design, the construction of the works, or, more commonly, in the maintenance of valves, gates, hoists, cranes, and other movable devices that become inoperable, usually because of poor maintenance (Figure 21).

Figure 21. A sluice gate valve at Barna Dam in Madhya Pradesh that has not been operated in many years. Sediment deposits in the reservoir have blocked the sluice inlet.

The consequences of ageing gates and other hydro-mechanical gear depend largely on the purpose of the equipment; that is, whether it is to control the discharge from an overflow spillway, an intake structure, or through other outlet works (Figure 22).

Figure 22. Leakage and flaking of concrete beneath the trunion of a radial gate at Bennithora Dam in Karnataka because of deterioration of lift joints from large daily temperature variations and chemical action.

Inadequately designed spillways can pose a serious threat to dams, appurtenant works, and to people living downstream from the dams. When designing spillway gates to operate reliably in extreme weather conditions, system operation should include appropriate redundancy to provide a sufficient margin of safety.

Failure of outlet works can lead to serious consequences resulting in uncontrolled release of a large volume of impounded water. Such releases can create severe flooding and damage powerhouses and other appurtenant works located downstream from the dam.

Malfunctioning of gates and other discharge equipment are detected by visual observation. Remedial measures for this ageing scenario include 1) repair of the damage caused by poor design, maintenance, or construction, and 2) improved maintenance to guarantee that the equipment will always be in a serviceable condition in the future.

Excessive Flow

Insufficient capacity of outlet works to discharge a large flood safely is another appurtenant works ageing scenario. This situation might be created because 1) the flood exceeds the design discharge capacity, 2) the discharge capacity is temporarily reduced because of malfunctioning control equipment, 3) the dam overtops, the frequent outcomes being breaching of earthen embankments, flooding of powerhouses at the foot of the dam, and erosion of foundations at the toes of concrete structures.

As hydrological and meteorological knowledge related to the occurrence of large floods improves, required inflow design floods for a dam may be revised resulting in existing spillway design capacities becoming deficient.

The scenario of excessive flow is detected by the performance of the discharge works during large floods, and by revision of their design and construction conditions as required to satisfy present day standards, particularly in regard to the inflow design flood, which is usually the Probable Maximum Flood (PMF) for large dams. The revised PMF for Hirakud Dam in Odisha (Figure 23) requires the spillway capacity to accommodate an additional 20,000 cubic metres per second.

DRIP Dam Rehabilitation

Without proper maintenance, repair and rehabilitation, as a dam ages the risk of failure will increase. Effective dam inspection programs routinely identify deficiencies at dams, but inspections alone are not a remedy for these deficiencies. Responsibility for maintaining dams lies with dam owners, many of whom cannot afford to finance needed repairs. Consequently, delays in repairing unsafe dams increase the probability of tragic yet preventable disasters.

Inadequate maintenance of some DRIP dams and appurtenant works, primarily because of lack of adequate resources and systematic assessment and monitoring, has resulted in deteriorated structures. Keeping in mind that many of the DRIP dams are composite structures composed of both concrete and masonry sections flanked by earthen embankments, the types & numbers of rehabilitation projects being carried out under DRIP are summarized in Figure 24 for concrete and masonry gravity dams and in Figure 25 for embankment dams.

At concrete gravity dams, repairs to foundation drains (mostly reaming to unclog them) and to

Figure 23. The revised inflow design flood for Hirakud Dam in Odisha requires and increased spillway capacity of 20,000 cubic metres per second.

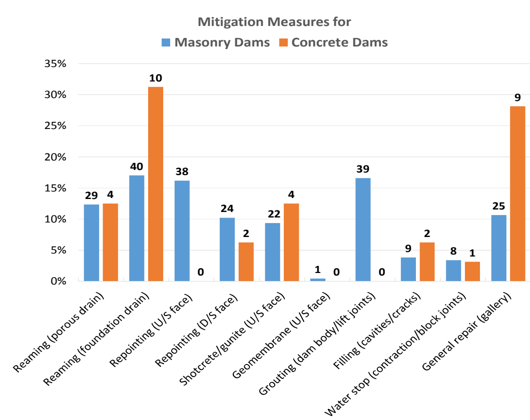

Figure 24. Summary of the types and numbers of rehabilitation projects proposed for DRIP concrete and masonry gravity dams.

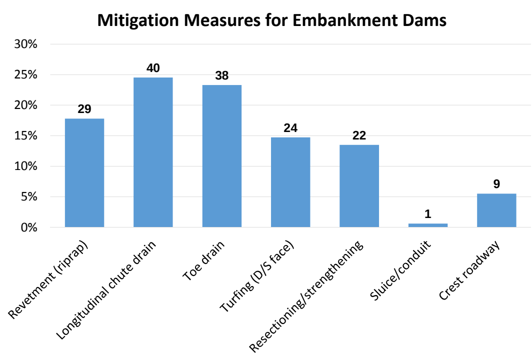

Figure 25. Summary of the types and numbers of rehabilitation projects proposed for DRIP embankment dams.

galleries where excessive leakage has created a variety of problems) are the most common remedial measures. Masonry gravity dams also require substantial foundation drain cleaning along with grouting of the dam body and repointing of their upstream faces to reduce seepage. Major rehabilitation efforts include grouting of the dam body as required at Chimoni Dam in Kerala (Figure 26).

Figure 26. Chimoni Dam in Kerala has been thoroughly investigated for dam body seepage through 3D Sonic Tomography and is being rehabilitated by large scale grouting.

Figure 27. Profuse leakage from the aged gates of the Krishna Raja Sagar Dam, Karnataka

A few of the DRIP dams have obsolete systems of gates, valves, and hoisting equipments, and in some such cases they have deteriorated beyond economical repairs. The sluice gates, numbering more than 150, of the prestigious Krishna Raja Sagar dam of Mysore represents one such case where a large scale hydro-mechanical rehabilitation work will be undertaken (Figure 27).

Most of the DRIP dams are in need of modern instrumentation to monitor and record structural behavior, displacements, seepage, and related hydro-meteorological and seismic factors, which would help detect the effects of ageing and forewarn dam operators of possible risks.

Spillway capacities of many large dams are now inadequate because they were sized on the basis of scarce data and lower standards prevailing at the time of design. Evaluation of dams included in the DRIP program shows that existing spillway capacities are deficient for three out of every four based on revised inflow design flood requirements (Figure 28).

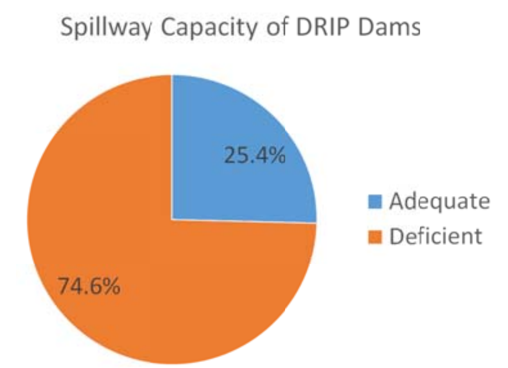

Figure 28. Nearly three out of four DRIP dams have insufficient spillway capacities.

Emergency Action Planning

In addition to ensuring safety by proper upkeep of India's ageing large dams, it is also necessary to prepare to face any emergency caused by a dam failure. For this reason, Emergency Action Plans (EAPs) need to be prepared for all large dams.

An EAP for a dam is a written document prepared by the dam owner, or the dam operator, describing a detailed plan to prevent or lessen the effects of a failure of the dam or appurtenant structures. An EAP is not a substitute for proper maintenance or remedial construction, but it facilitates recognition of dam safety problems as they develop and establishes nonstructural means to minimize the risk of fatalities and reduce property damage.

The EAP is intended to interface with the emergency operation plans of other local, District and State agencies to ensure effective and timely implementation of response action. Every EAP has to be thus tailored to site-specific conditions and to the requirements of the dam owning/operating agency and the local emergency management authorities.

DRIP has prepared a document titled *Guidelines for Developing Emergency Action Plans for Dams* (Figure 29) that defines the requirements of an acceptable EAP and facilitates its preparation, distribution, annual update, testing, and periodical revision.

Adequacy and accuracy of primary data is important in formulating an EAP and in determining the severity of the situation during a dam failure or a dam incident. Most EAPs will typically have several different alert levels to allow emergency responders to take appropriate actions depending on conditions at a dam. A template is provided in the *Guidelines* to help dam owners prepare EAPs that follow a basic five-step response process.

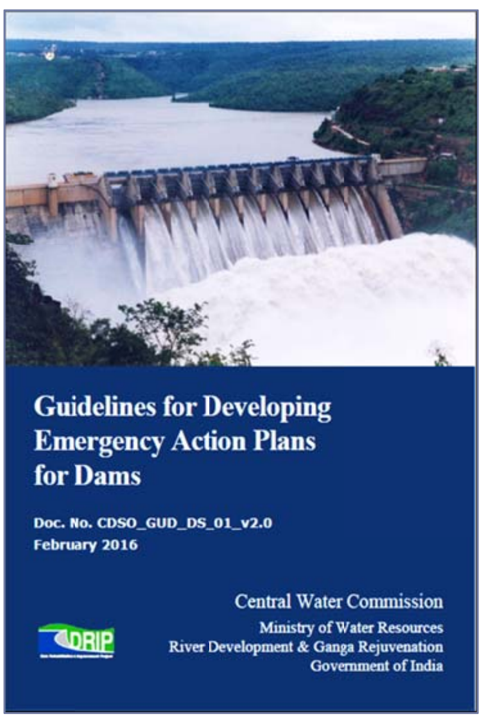

Figure 29. Guidelines for developing emergency action plans for dams have been developed by DRIP for use by dam owners and others.

Conclusions

As India's large dams age and development continues in downstream floodplains, their structural integrity will become a more significant public safety issue. Regardless of whether dams were constructed to withstand an earthquake or flood of "appropriate" magnitude, they may have age-related deficiencies that need to be corrected to maintain current levels of safety. Therefore, it is likely that the frequency of requests for safety inspections and rehabilitation activities will increase.

Prevention and mitigation of ageing will be achieved best through carefully thought-out designs, construction of high quality, and well-managed operation and maintenance programs. A well-planned and performed monitoring program based on data collected and processed by modern instrumentation is the key to early detection of ageing scenarios. Regular, orderly, and efficient inspections followed by thorough maintenance are critical elements of an effective dam safety program.

Although most dam owners have a high level of confidence in the structures they own and are certain their dams will not fail, history has shown that on occasion dams do fail and that often these failures cause extensive damage to property, and sometimes loss of life. Dam owners are responsible for keeping these threats to acceptable levels.

The Central Dam Safety Organization (CDSO) provides technical and managerial assistance to dam owners and State Dam Safety Organisations (SDSOs) on proper inspection, operation, and maintenance of large dams and appurtenant works. To a select number of distressed dams, financial assistance for their rehabilitation is also rendered under the DRIP program. In addition to ensuring safety by proper upkeep of the dams, the CDSO also helps dam owners and SDSOs prepare to face any emergencies caused by a dam failure.

Dam Safety Rehabilitation Directorate
Central Dam Safety Organisation
Central Water Commission
3rd Floor, New Library Building (near Sewa Bhavan)
R. K. Puram, New Delhi – 110066
Email: dir-drip-cwc@nic.in
Phone: +91 112-616-8903
Website: www.damsafety.in

Central Dam Safety Organisation

Central Water Commission

Vision

To remain as a premier organisation with best technical and managerial expertise for providing advisory services on matters relating to dam safety.

Mission

To provide expert services to State Dam Safety Organisations, dam owners, dam operating agencies and others concerned for ensuring safe functioning of dams with a view to protect human life, property and the environment.

Values

Integrity: Act with integrity and honesty in all our actions and practices.

Commitment: Ensure good working conditions for employees and encourage professional excellence.

Transparency: Ensure clear, accurate and complete information in communications with stakeholders and take all decisions openly based on reliable information.

Quality of service: Provide state-of-the-art technical and managerial services within agreed time frame.

Striving towards excellence: Promote continual improvement as an integral part of our working and strive towards excellence in all our endeavours.

Quality Policy

We provide technical and managerial assistance to dam owners and State Dam Safety Organisations for proper surveillance, inspection, operation and maintenance of all dams and appurtenant works in India to ensure safe functioning of dams and protecting human life, property and the environment.

We develop and nurture competent manpower and equip ourselves with state of the art technical infrastructure to provide expert services to all stakeholders.

We continually improve our systems, processes and services to ensure satisfaction of our customers.

Dam Rehabilitation & Improvement Project