A Study on Challenges in the Rehabilitation of Large Masonry and Concrete Dams

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Abstract. Large dams retain enormous volume of water intended for various purposes. The design, construction, operation and maintenance of these special structures are of paramount importance considering its uses and safety. Safety of the dam is to be ensured throughout its’ life from structural, hydrological and operational perspectives as its failure would be catastrophic. Periodical safety inspections, review on safety, dam health monitoring as well as risk assessments are measures to ensure safety of these large structures. Ageing of dams is a concern in dam safety as there can be inadequacies or deficiencies with respect to structural, hydrological and operational requirements. Revision of relevant codes of practice/standards also may necessitate review and strengthening. As such, these structures are to be rehabilitated to the prevalent standards and maintained healthy to continuously derive the benefits envisaged during construction. Rehabilitation of dams aims to bring it back to a good condition and ensure that it does not pose a risk to the stakeholders downstream. The process involves various systematic procedures such as review of structural design, review of design flood and diagnosis using non-destructive tests to detect possible deterioration in its health, etc. As per recent statistics, more than half of the large dams in India are more than 25 years old. In this paper, a review of aspects such as challenges, considerations as well as various factors involved in the effective implementation of rehabilitation/strengthening is presented. Certain case studies of rehabilitation work undertaken under the on-going Dam Rehabilitation and Improvement Project in India are cited to bring forth the importance of such measures. As dams play crucial role in the prosperity of the nation, they are to be maintained for an endured life without jeopardizing the safety of the structure. In that perspective, rehabilitation of dams or its strengthening process is extremely important.

1. Introduction
Development of Water resources is a portfolio of high priority for all governments as this resource having vast potential in many areas is limited. Sustainable economic growth, through improvement in irrigation, hydro-electric power generation, flood control, and potable and industrial water supplies, etc., besides many other uses can be derived from the water available to a country by careful and scientific manner. Dams play a vital role in the precipitous and persistent growth in the above sectors. Having identified the potential of dams, the respective Nations are keen to maintain these vital structures contributing positively to the economy, safely. Globally, India is in the third position for having most number of large dams. China and the United States rank first and second respectively. Though the
initial constructions for impounding the water were earthen embankments and masonry, the twentieth century found a growth in the number of concrete and masonry dams by virtue of advancements in construction materials, methodology and technology. As per the statistics (Table 1) by ICOLD, 65% of the reported large dams in the world are earthen dams [1]. The operation and maintenance protocols of concrete and masonry dams are different from earthen dams and the present discussion is confined to concrete and masonry dams.

| Sl. No. | Type of dam         | Number |
|---------|---------------------|--------|
| 1       | Earthen dams        | 37537  |
| 2       | Rockfill dams       | 7729   |
| 3       | Gravity dams        | 8115   |
| 4       | Buttress dams       | 415    |
| 5       | Barrages            | 299    |
| 6       | Arch dams           | 2352   |
| 7       | Multiple arch dams  | 129    |
| 8       | Others              | 1409   |
| **Total** |                     | **57985** |

2. Dam engineering

Dam construction using stones dates as early as 2900 B.C.-2600 B.C., in Egypt. Later, the Romans and the Mongols started constructing dams. The 55m high arch dam constructed in rubble masonry in 1300 AD at Qum is believed to the oldest surviving arch dam. Civilizations and Nations realised the need of dam construction and accordingly the world saw more dams coming in. Till, 1850, there were no rational criteria for design of dams but the theories by M.de Sazilly, in 1853 that the pressures within the dam have to be within limits and dimensions are important for prevention of sliding, and the conceptualization of the middle third criteria after another 25 years, by W. J. M. Rankine paved way for more gravity dams. The construction of large dams capable of storing large volumes of water is a result of technological advancement imbibing of relevant theories in the conception, analyses, design and execution stages. The dam engineering involves selection of suitable site, investigation of geology for foundation preparation, and structural as well as hydrological analyses. The calculation of risks involved, its’ mitigation measures, inspection and reviews for confirming whether the structure would safely route the flood from the rainfall intercepted by the catchment, maintaining seepages, stresses, uplift and movements within limits, etc. are relevant in dam engineering. Evaluation of behaviour of dams requires knowledge from a spectrum of technologies and practices exercised by Engineers over past many years. The dam engineering takes into consideration new perspectives on earthquake engineering and its’ dynamics, improved methodology for foundation treatment, advancement in soil mechanics/geotechnical Engineering, seepage analyses using state of the art methods, stability analyses, advances in concrete dam technology, refined techniques for hydrologic and hydraulic analyses, state of the art instrumentation, employment of newer materials for construction as well as for rehabilitation such as synthetic membranes, real time data acquisition, dam operations and management etc.[2].

Dam engineering forms a vital part in the history of civilization as reservoirs were constructed by various civilization for water supply and irrigation using different material, viz., earth, wood, stones, fills of various length, width and height. The failures of the past helped devise new theories and efficient methods. Dams of various type and shapes were constructed over the past. Rectification and rehabilitation works were attempted on the dams of the past. De-siltation, control of seepage, drainage systems for reducing uplift etc. were identified as a rehabilitation measure of the existing dam. The Couzon dam constructed in 1811, was to be rehabilitated in 1896 to control seepage and sliding and later it remained in service without trouble. The Aswan dam in Egypt, 20m high, constructed in 1902 was of quarried granite mass, which was raised to 27m in 1912 and in 1933 to 53m height above foundation [3]. As various types of deficiencies are identifiable, remedies can also be systematically executed as the rehabilitation and it has become an indispensable part in dam engineering.
2.1. Dam safety

Dam safety comprises of structural safety, surveillance, maintenance, and emergency planning which will help minimise the risks if it cannot be eliminated. ICOLD recognises certain aspects as the pillars of dam safety, they are, structural integrity of dams, the routine surveillance and maintenance programme for early detection of risks, instrumentation and monitoring plan throughout the life-span of the dam, addressing of design-intrinsic risks, regular review and updating of natural hazard risks as they change with time, emergency planning, sharing lessons learned to benefit the entire industry, comprehensive dam safety approach for minimizing the risk, the owners’ ultimate responsibility of the dam, prominent role of regulatory authorities etc., besides emphasizing the international perspective to dam safety as it would be able to impart the experiences as well as best practices worldwide to the designers, dam owners and authorities concerned [4].

3. Rehabilitation of large dams

Safety of these structures contributing vitally to the economy and well-being of the respective nation is most important on two aspects, viz., for deriving the targeted benefits uninterruptedly and to get rid of the risks to the life and belongings of stakeholders at the downstream. Constructing a new dam involves many challenges and impediments, and this emphasises that the existing are to be managed healthy and safe for prolonged use. Many existing large dams are having various deficiencies such as structural and hydrological besides deteriorations due to ageing and operational shortcomings. Rehabilitation of a dam is often referred to as, bringing it back from a distressed state to the original state and certain improvement for meeting requirements by virtue of changes in the safety criteria over the time. Methodology of rehabilitation will vary for each dam. Implementation and planning of rehabilitation of a concrete or masonry dam depends on field investigations, materials for rehabilitation etc. The safety evaluation of an existing dam should recognise problems and suggest remedial measures, restrictions in operations, modifications (if needed), besides doing analyses and studies to determine solutions to the problems [5]. Each year, the number of aged dam is increasing; India, the 3rd Country having most number of dams, presently have 5334 large dams[6], of which 67 are constructed prior to the year 1900 whereas there are 304 dams constructed during the period 1901 to 1950 (Figure 1) and every year this count is increasing considerably. Over 75% of its’ large dams are more than 20 years of age. These ageing structures require a systematic rehabilitation, consisting of deciding their needs, design and implementation of rehabilitation activities with adequate control on the quality.

![Figure 1. Growth in the count of large dams in India](image)

Suitable rehabilitation measures after adequate studies can negate the deficiencies due to ageing and the inadequacies due to revisions in standards/criteria/guidelines on dam design, operation and their safety operations. Deterioration due to environmental actions, deterioration of equipment due to continuous use, becoming unserviceable due to prolonged operation, destruction caused by natural actions such as earthquakes, floods, or land-slides, destruction caused by sabotage and war etc. too are deficiencies or inadequacies.
3.1. Need of rehabilitation of dams
Deterioration of concrete and masonry due to ageing is a major concern to dam owners and stakeholders downstream and it warrants for rehabilitation. The thermal effects due to the temperature gradient between various parts of the body, alkali-aggregate reaction and other chemical reaction due to presence of various chemicals in aggregates and cement, leaching actions, climatic actions such as freezing-thawing, etc. are various factors that cause deterioration of dam body health. Deterioration of foundation may also be caused due to the loads acting, properties of the foundation strata/geological conditions etc. Deterioration of dam body and foundation may lead to cracking, stability problems, increased seepage and uplift pressures. These causes and effect are to be investigated thoroughly before rehabilitations are planned and implemented. As per a study of ICOLD [7] on the deterioration of concrete and masonry dams, summarised the following scenarios (Figure 2-Figure 4):

![Figure 2. Foundation rock mass cases.](image)

![Figure 3. Ageing scenario pertaining to:](image)

![Figure 4. Dam body (Concrete/Mortar/Stone) cases.](image)

Dams require rehabilitation mainly for two reasons, viz., for dealing with the effect of the ageing process and for conforming with the requirements of new standards introduced. Large numbers of dams worldwide were subjected to rehabilitation to meet the stability criteria against flood and earthquake as well as uplift criteria. Mainly areas subjected to rehabilitation, are foundation, dam body and the increased stability. Loss of strength for the rock mass foundation is a major concern related to stress reversals in the foundations due to fluctuations in hydraulic gradient due to the water level in the reservoir. Stress reversal may cause the joint infillings to wash away, deformation to foundation, moving of joints in rock, and crack initiation and propagation. Monitoring is necessary as this will happen over a large period of time and as such, seepage, uplift pressure, and inelastic foundation displacements are to be monitored using instrumentation data. Review of stability owing to revision in design flood, review for increase in spillway length to route the increase in flood, if any, change of hazard zones and revision of standards for earthquake resistant design, etc. are important aspects in deciding rehabilitation. Seepage in concrete and masonry dams is a problem often met by dam owners and this is caused by factors such as cracks, poor lift joints, deterioration of concrete material, deterioration in the masonry pointing at the upstream face causing the joints to open up, poor block joints/transverse joints, etc. Though evidence to seepage can often corroborate with wetness, sprouting, calcination, increased flow in the drainage gallery, in many cases, the exact source could not be easy to detect. Seepage if unchecked, undetected and not remedied can lead to undesirable results.
3.2. International practices

Various measures for the rehabilitation of large dams use technology, materials, processes, methodology, and literature available from acclaimed sources. International organizations such as, ICOLD, United States Society on Dams, Bureau of Reclamation, US Dept. of the Interior (USBR), U.S. Army Corps of Engineers, Federal Emergency Management Agency, Federal Engineering Regulatory Commission, British Dam Society, ASCE, Institution of Civil Engineers, Bureau of Indian Standards, the Central Board of Irrigation & Power, India(CBIP) etc. give useful information on various loads acting, criteria, guidelines for analyses and investigations/inspections to be done as well as rehabilitation aspects of dams through their websites and publications.

Materials for rehabilitation

Repair works, for the rehabilitation and methodology to be adopted shall be decided with suitable material and for the same, experience, guidance based on relevant codes such as, ASTM, ACI, EN, BIS as well as relevant literature from ICOLD and other internationally acclaimed authorities cited in paragraph 3.2 can be made use of. The selection of a repair material and the methodology depends on the causes of distress, type and extent of deterioration in concrete or masonry and their symptoms, etc. For a concrete dam, materials such as high performance concrete, cementitious mortar, free flowing micro-concrete, epoxy based compounds, fiber-reinforced as well as polymer concrete, coatings, geo-synthetics and sealing system with geo membrane etc. can be used. Various bonding agents matching to the materials, grouts, materials for patching and resurfacing, steel liner, etc. will be used as necessitated by the rehabilitation. Likewise, the materials for rehabilitation of masonry dams depending on the problem, the material can be decided.

High performance concrete having high erosion resistance finds use in repair of spillways (crest, and glacis, etc.) structures for energy dissipation, silt excluder tunnels and tunnel spillways, etc. As such, the coarse aggregates should have the required abrasion value, crushing value, and impact value. The cementitious mortar used for the structural and non-structural use should possess the required physical and mechanical properties as well as bonding characteristics matching for the parent concrete, in case of repair application. The European standards, such as EN 1504-1 to EN 1504-10, EN:12190, EN:1015-17, EN:1542, EN:13295 and EN:13412 etc. stipulates various performance characteristics, test methods and requirements in those cases. Such cementitious materials possessing UV resistance, compatibility in thermal properties, high strength in compression and impermeability are now being used in dams of masonry also for pointing of the damaged upstream face to control seepage[8]. Quality control for its’ storage, proportioning, application (methodology), testing etc. are areas of concern and are matters requiring utmost care and diligent supervisory control. The cementitious repair mortar, satisfying with these properties is of crystalline technology or polymer based additives with the cement. These materials are often used in rehabilitation works at upstream sides of the dam, rectifying damages in spillway piers, etc.

Various types of micro-fine concrete can be used for the repairs of deteriorated reinforced concrete zones where accessibility and compaction by vibration are hindered. The cement, graded aggregates, additives, fillers etc. used must be capable of imparting the strength and non-shrink characteristics. Various types of epoxy compounds find its’ use as sealants, bonding agents and patching materials, grouts, binders, etc. due to their favorable performance characteristics such as adhesion, high strengths in compression and tension, rapid hardening, bonding characteristics in damped concrete as well as under water, chemical resistance & moisture resistance etc. ASTM C881 gives the technical specifications of various types of epoxies for load bearing areas /non-load bearing situations whereas ASTM D 1084, ASTM D695, ASTM D638 and ASTM C882 gives the mechanical properties such as viscosity, compressive, tensile and bond strength etc. [9-13]. Difference in thermal expansion of epoxy compounds and concrete, peeling off the repaired layer from surface due to temperature stresses at the boundary between concrete & epoxy mortar, decomposition due to ultraviolet rays when exposed to sunlight are challenges in using these kind of repair material and hence require strict quality control.

Steel liners and fiber reinforced concrete can be used for the repair or rehabilitation works where cavitation, erosion and abrasion etc. are likely. Steel liners even though offers resistance to cavitation and abrasion, fixing of plates against old concrete surfaces are challenging task as fixing using anchor rods and back filling/grouting the voids behind the plates, quality of the steel plate against pitting, etc.
are factors affecting prolonged life. Various types of fibers can be added to the concrete to increase the
strength and life of the repaired portion. Polymers can also be used in repair concrete, to improve their
properties such as bonding and accordingly there are polymer, polymer modified and polymer
impregnated concrete. The improvement in properties depends on the additives and admixtures used.
The challenge in using these types of concrete is that they are hazardous and expertise is required in
preparation and application.

Geo-synthetics or Geo-membrane sealing systems are used in rehabilitation of water retaining
structures for checking seepage through the body. This technology can be used in various types of dams,
viz., embankments, masonry as well as concrete. Primary requirements for these materials to work
efficiently are impermeability, flexibility to use, mechanical strength, resistance to frost and heat,
easiness for industrial production and easy workability [14].

5. Rehabilitation planning
Rehabilitation on dams should be preceded by preliminary as well as detailed field investigations (for
remedial actions) which include inspection of the expert panel for evolving recommendations and the
minimum design studies. The minimum design studies include the design flood review (DFR)(In India,
it is for the PMF, Standard Project Flood or 100 Year return Period flood). The ICOLD list the above
criteria for various other countries [15]. Maximum water level, free board available and the demand for
additional spillways, if any shall be obtained through routing of revised flood. Selection of site for
additional spillway, if necessitated, investigations for assessing topographical and geological conditions,
stability analyses of the dam including seismic review of the dam-spillway structure etc., have to be
carried out using actual material properties.

Worldwide, it is a good practice in monitoring for dam safety that the dam inspections of the
components, viz., dam, reservoir, downstream areas etc., are being carried out on a regular basis and in
case of any unusual behaviour, expert panel will have independent inspections. Dam owners shall have
monitoring equipment for re-assessment of the structural behaviour of the body and foundations, regular
evaluation of data measurement and the structural behaviour reports. Periodic inspections &
maintenance will help in reducing major unexpected rehabilitation works. In case of large scale
rehabilitation, financing arrangements for the rehabilitation work is equally important.

5.1. Design aspects
Rehabilitation in dams is generally based on the recommendations brought out as per the observations
in various inspection reports. Reports of earlier inspections, viz., comprehensive and others, physical
condition and performance of the dam body, appurtenant structures as well as hydro-mechanical
components, measurements taken from instrumentation in the dam, photographs taken periodically,
designs & construction drawings, properties of materials used, particulars of any earlier dam incident
and corresponding rehabilitation done so far, risk analysis and risk assessment if any, etc. are factors
affecting the choice of a rehabilitation. Continuous structural monitoring utilizing additional
instrumentation, inspections etc. will also be necessitated. Further studies & investigations to determine
the actual area affected & rehabilitation plan, measures to be taken for lowering of reservoir level & for
handling of emergent situations, repairs of spillway gates, if required, etc. are also pertinent. Review of
design flood studies which decide the spillway capacity, revised water availability studies which decide
the hydro-electric potential, irrigation, water supply, impact of projects built recently on the upstream(if
any), experience of the hydro-mechanical parts operating personnel, changes, if any, in river
morphology etc. are relevant. Rehabilitation works shall take into account construction techniques, the
effect of the methods like blasting, pre-stressing and grouting, etc. on the existing structure, effect of
using materials of different properties vis-à-vis the original construction materials on the dam, measures
for environmental impact mitigation etc.

5.2. Construction aspects
Rehabilitation work requires a good contract in which the work is unequivocally defined so that surprises
are avoided to the extent possible. Rehabilitation work can be implemented through item rate contract,
turnkey contract or EPC contract. Pre-qualification documents are to be structured carefully for
arranging the rehabilitation work without conflicts. Items of works of special nature should preferably
be implemented with specialised agencies having expertise. Performance warranty for the specified duration, construction supervision, Quality Control and Quality Assurance are aspects for careful consideration during the implementation stage.

5.3. Risk management

Through risk assessment in dams which are to be rehabilitated helps the dam owner to prioritise them for effectively reducing the risk, integrating all the dam safety aspects in the assessment (i.e. aspects such as dam safety monitoring, health of the dam, operation and maintenance, mitigation measures such as emergency action plan, rules of operation etc.) which normally are analysed as separately. Various methodologies of risk analysis [16] are to be adopted for supplementing with the direct approach of analysis, and reporting after visual inspection.

5.4. Field investigation and minimum design studies

Inspections evaluating the overall condition of the dam along with detailed studies and additional exploration or analyses substantiating the general assessment already conducted are necessary to evaluate the safety of the dam before proceeding with the rehabilitation process. Minimum design studies, as mentioned in paragraph 5.1, would be necessitated.

5.4.1. Investigation and testing

Tests or investigations to be carried out for salient parameters depend on the inspection observations and considerations according to the problem. It would sometimes require extraction of representative cores from the concrete/masonry dam for carrying out certain tests. Indications on certain parameters could be obtained through non-destructive testing. Test for deciding parameters such as density, compressive strength of concrete/mortar in masonry, static as well as dynamic modulus of elasticity, splitting tensile strength of concrete, permeability of concrete/masonry, chloride content & pH of concrete, corrosion activity in concrete, analysis of the reservoir water/seepage water, investigations for seepage path or permeable locations in the dam for planning directional grouting or conducting a seismic study for the site-specific seismic parameters, are a few important activities to name. The tests shall conform to relevant national/federal/international standards as applicable. The Indian standards such as IS 13311-Part1, IS 516, IS 5816, IS 11216, IS 456, IS11216, IS 5529 etc. can be referred to for the tests mentioned.

5.4.2. Geophysical explorations

In masonry or concrete dams, determination of seepage zones or seeping paths is an important investigation that decides the objective and methodology of rehabilitation. Various types of geological exploration methods (seismic refraction method etc.) and other methods utilizing the principles of geophysics are capable to determine seismic parameters as well as relevant details pertaining to the existing conditions of the concrete/masonry dam. Electrical resistivity, Sonic tomography (Plate 1 &2), ground penetrating radar, streaming potential are a few methods used in analyzing the condition of existing dam. In sonic tomography, the velocity contour maps in longitudinal and cross section would be able to interpret for desirable remedial action for rehabilitation works.

6. Role of Instrumentation in Large dams

Lack of proper and timely instrumentation of dams is a real challenge in the dam safety monitoring and implementation of timely rehabilitation measures. Instrumentation in dams helps the dam owner or the administration, in safety evaluation of the existing dams, for obtaining early warnings of any emergent distress on the dam health, in verification of the design and the actual behaviour of the dam with respect to the designed and for more realistic analyses, etc., using the actual observations from the instrumentation. The type of measurements from the instrumentation in dams include strain and stress measurements, differential displacements with respect to vertical and horizontal, relative and rotational movements, temperature measurements, seepage measurements, uplift pressure measurements, piezometer measurements for pore-water pressure, geodetic measurements for movement of dam, abutments, foundation and seismic measurements that give valuable inputs to study the ground motion due to any seismic event and effects of the same on the dam. ICOLD bulletin [17, 18] summarises the different types of dam instrumentation.
Plate 1. Geophysical investigation crew member for sonic tomography imparting source of sound waves at the upstream face of the masonry dam.

Plate 2A. Acquisition station. Plate 2B. Accelerometer sensors.

In order to monitor the loss of strength of the foundation, seepage, uplift pressure, and inelastic foundation displacements are to be measured. The quantity of seepage, origin, quality, presence of solids in the water, the origin of the same, etc. are to be gathered and analysed. Reliable and stable piezometers shall be installed at distinct points to measure the uplift pressure on a long term basis. Geodetic surveys, observation by pendulum, inverted pendulum moored deep bottom of dam, etc. are useful in detecting the displacement of the rock foundation due to loss of strength. Foundation problem, if any, have to be identified timely through expert intervention. Grouting is a remedial measure for strengthening foundation rock whereas problems due to uplift can be improved by grouting and appropriate drainage measures. Seepage and uplift pressure measurement during the operation of the dams will give light to erosion and solution of foundation rock also [8].

The selection and installation of various types of instruments, location, their measurement and frequency of measurement and analyses [19] are important aspects to the dam safety management (Figure 5-6). The faulty or non-working instruments, absence of periodic measurements as per the desired frequency, lack of proper maintenance as well as analyses by qualified Engineers are impediments in getting timely data for evaluating the safety assessments and deciding the rehabilitation measures. In order to have accurate and reliable analysis for a sensitive structure like double curvature arch dam, comprehensive analyses for chemical and physical properties of concrete need to be done. Field investigations include NDT such as tests on UPV, carbonation, in-situ moisture content, resistivity, half-cell potential, air permeability etc., whereas laboratory tests include tests for strength in compression and tension, poisson’s ratio, modulus of elasticity, drying shrinkage, moisture movement and thermal expansion of the aged concrete [20].

Figure 5. Layout for triangulation measurement: (1) targets fixed on dam surface; (2) theodolite; (3) base line, measured; (4) base line, computed; (5) sight lines [19].

Figure 6. Layout for collimation measurements used for an arch dam [19].
7. Some noteworthy past instances of dam rehabilitation

Revision of data, guidelines, standards, methodology, etc., may require an increase in storage capacity; there can be decrease in useful storage due to silting and there can be situations where the ageing had caused deterioration or loss in strength. In all these situations, strengthening of the dam or raising the height of the dam would be necessitated to conform to the safety requirement insisted by the standards, as realised through the safety evaluation. If these vital structures are not strengthened or rehabilitated, for exploiting their uses, they will stay vulnerable to failures and will be a potential source of risk to the stakeholders downstream of the dam. Various methods and techniques can be used for the rehabilitation. Some of the methods used in the past for raising the concrete dams are, adding weight to the dam on its’ top so as to bring the resultant within the middle third, give earth backing, by providing an embankment downstream for the parallel heightening or cable anchoring from the foundation by pre-stressing through the Coyne method (Andre Coyne, 1932) in which the heel region is subjected to compression by applying a vertical force at top of the dam. As per the literature, earth backing or embankments at downstream side were provided for 61m high Talakalele dam in Sharavathi Hydel Project, 30m high Stettynskoof Dam, South Africa whereas there are many instances of adding concreting at downstream side(parallel heightening), viz., Aswan dam, 42m high Loskop Dam(Figure 7)which is raised by 9m, the Grand Dixence Dam(Figure 8), which had increased its’ height up to 167m first and then to the full height of 280m, Guri dam in Venezuela which was raised from 100m to 162m height from the lowest foundation level[21]. The 103m high Koyna dam in India, a gravity dam with rubble-concrete construction, which suffered an earthquake measuring 6.5-7.0 in magnitude on December 11, 1967 were to be subjected to short term and long term rehabilitation measures. The long term rehabilitation was by providing buttresses at the downstream and the contact between the buttress and old surface was grouted with cement for monolithic action [21]. The 59.3m high(max.) constant radius concrete arch, Gibraltar dam in California, was strengthened against the possible tensile stresses and cracking against MCE and to compensate for the loss in storage due to sedimentation, by providing a roller compacted concrete (RCC) gravity section at the downstream.[21].

In all those cases, the issues addressed were the load distribution between the old and new concrete, bonding and the shear stress at the interfacing plane. The difference in Elastic modulus of old and new concrete, differential stresses due to temperature effect, increased uplift pressure due to increased height etc., also are matters of concern. The solution to uplift issue requires proper and sufficiently deep drainage system. The surface preparation for sufficient bonding, contraction joints in old and new structure, differential settlement due to addition of weight etc. are to be studied using appropriate modelling techniques before being implemented. FEM techniques are capable of simulating the scenario and predicting the structural behaviour of the combined structure before the rehabilitation is implemented. Though pre-stressing by cable anchoring are used in various dams, the maximum height of dam recommended is 60m, beyond which the application of pre-stressing force would increase considerably besides the practical difficulty in constructing anchorages[21].
8. Some recent cases of rehabilitation from India

Certain rehabilitation works require extensive field investigation, studies, comprehensive analyses and approvals & clearances as it involves administrative, engineering, land, forest, environmental aspects before entering into real implementation for which more time, money and other resources are required. Examples of such important and challenging rehabilitation attempts in India in recent past include, de-siltation of Kundahpalam, Pillur, Papanasam dams in Tamil Nadu, spillway requirement for the acclaimed Hirakud dam, Odisha, rehabilitation of gates and hoists –almost 100 year old– of the famous Krishnarajasagar dam, Karnataka and analyses for unusual behaviour in Idukki dam, etc.[22]. Environmental and social management framework requiring satisfactory mitigation measures is an important and challenging task in major rehabilitation work such as construction of additional spillways to cater to the increased design flood; the rehabilitation and resettlement of the projected affected people, as well as the environmental issues involved in the de-siltation of reservoirs to remove the sediments deposited that reduces the useful storage are challenging task requiring careful implementation.

8.1. Geo-membrane in masonry dams

PVC composite geo-membrane and geo-textile was used for the waterproofing system in many concrete and masonry dams against the leakage of upstream reservoir water through the dam body. There are various instances where the upstream faces of the dam were to be installed with a PVC composite geo-membrane or geotextiles as a rehabilitation measure against the seepage related issues in such dams all over the world[14]. The Kadamparai dam in TamilNadu, installed with PVC geo-membrane system were reported to have reduced the seepage by a large measure. In Kadamparai dam waterproofing for an area of 17,300m2 was reported to have completed in 3 months and six weeks [23]. The important challenging aspects to the project authorities and installation team would be the need of meticulous planning for activities such as depletion of the reservoir as well as thorough upstream face preparation before installation of the system, ensuring of strict quality control in the material and its’ installation besides proper design and installation of the drainage, perimeter sealing and anchoring system. After Kadamparai dam India, the Servallar dam (Figure 9) and Upper Bhavani dam in Tamilnadu are also being rehabilitated using geo-membrane sealing system(GSS) [24].

Figure 9. Kadampara dam upstream face, before, during and after installation [23].

8.2. Servallar dam

Heavy seepage of 742.65 litres/min.(lpm) with water level at +263.18 m were reported through the left flank portion besides leaching in the servalar dam, in Tamil Nadu, India. Raking and pointing using special mortar, guniting, etc. done were not able to control dam body seepage and to address the seepage issue through the left bank masonry joints, rehabilitation using PVC geo-membrane sealing system was adopted (Figure 10). Many challenges were experienced in the implementation which included, difficulties in depletion of the dam, excavation and de-silting of the sediments, unprecedented rain, monsoon, cyclonic rain, wind, adverse working conditions, agitation of local public etc. The work was delayed and implemented different compartments and different phases for obtaining dry working sessions, before it was completed. After completion, the project authorities reported that the leakage could be brought down to 30 lpm at water level +257.35m [24].
8.3. Cementitious material
Apart from PVC GSS, there are various other treatment systems of cementitious materials for upstream face treatment for checking seepage of water from upstream side to downstream through the dam body. They include crystalline technology and certain polymer-based materials. The important aspects in the effective implementation of these methods too are depleting the reservoir for treatment to extend up to the foundation level, strict quality control in material physical and chemical properties, storage, proportioning, curing as well as application. The Alamatti dam & Krishnaraja Sagar Dam in Karnataka and Anathode dam of Kerala are a few examples where such upstream treatments are taken up as rehabilitation measures. The upstream face treatments along with appropriately designed and implemented grouting are often suggested in such situations for getting better results.

8.4. Structural Analyses for rehabilitation
The rehabilitation process to the large dam structure many a times would require comprehensive structural analyses. The following cases are cited.

8.4.1. Konar dam. The 3682m long earth-cum-concrete Konar dam, Jharkhand, India completed in October 1955, consist of a 58 m high concrete gravity dam, 277m in length, flanked by earthen dam on both sides, three galleries, i.e. inspection gallery (+408.432 m), Access gallery (+ 391.668 m, and a gallery at lower elevations in foundation. About seven years after the completion, in 1962-63, the dam developed cracks on both d/s and u/s faces of the galleries in all the blocks. Cracks in the top gallery were wider ones than those in the two galleries below, and it expanded as time passed by, until it reported stabilised in 2010. Downstream slope of non-overflow portions of the dam developed surface cracks. Several studies to deduce the cause, nature, and behaviour of the cracks were conducted. Accordingly several measures adopted to deal with the situation. In order to device suitable rehabilitation measures, under the Dam Rehabilitation & Improvement Project (DRIP) in India and an exhaustive 3D and 2D finite element coupled thermo-mechanical analyses in ABAQUS v6.14-4 software environment, with the dam-foundation modelled as linear-elastic for materials, but geometry and contacts having modelled as non-linear, for investigation of its cracks, has been carried out[25,26].

The time consuming analyses simulating the existing condition confirmed the temperature effects as the predominant reason of cracking and suggested rehabilitation measures such as repairing of the cracks with low pressure normal grouting during the summer during which period the cracks are expected to be in fully open position with cementitious materials/mortar Class R-4 having specific properties conforming to British & European Standards BS EN-1504, restricting admixtures to shrinkage reduction only. The study recommended special type of painting on the exposed faces as well as downstream face to reduce the effects of solar radiation besides recommending for instrumentation for reservoir temperature measurement and for crack monitoring [27,8].

8.4.2. Idukki dam. Idukki dam, India’s only double curvature arch dam, is installed with 18 groups of instruments in electronic, mechanical, geodetic and seismic devices for measuring temperature, deformation, and seismic disturbances influencing the dam. Monument triangulation, Geodetic targets.
installed at predefined points, suspended pendulums, crest leveling, gallery leveling and crest collimation helps understand the dam behaviour [28]. Still, there were field investigations and lab investigations for identifying the various properties of the concrete and these parameters were used for the FEM study. The behaviour in stress and displacement at various salient locations were studied using 3D FEM analyses using ABAQUS software, and the thermo-static analyses ascertained the dam behaviour conforming to the instrumentation data besides the observation that results are more accurate when the effects of vertical joints are taken into consideration [29]. The study also recommended certain rehabilitation measures including painting with reflective properties on the intrados surface to control the thermal effects on the dam. A modernised instrumentation for real time structural health monitoring was also evolved after the study which will help the project authorities, a comprehensive dam monitoring.

8.4.3. Anathode- kakki dam. Seepage is to be thoroughly investigated at areas such as abutment and foundation areas, upstream and downstream faces of the dam and in galleries. Where the upstream faces of the dam and other suspected areas are not accessible even by divers, a remotely operated vehicle (ROV) can be deployed to investigate. Since the location of seepage was from deep and inaccessible areas of control gates and sluice gates under water, exploration using RoV will be able to locate the faults and designing suitable rehabilitation measures. Exploration of details of deterioration at the sluice area was done in Kakki, through the RoV (Figure 11 & Figure 12) using expertise. In case of severe seepage in masonry dams, geophysical investigations often will be able to locate seepage and seepage path for remedial measures, in which they use the principle of geophysics and mapping the structure using the state of the art technologies. There are instances in high concrete dams where installation of passenger lifts are impeded by leakages, in which cases, leakages into lift well are suspected to be from upstream block joints. Remedial measures can be done by systematically designed grouting (and reaming of drainage holes) in adjacent blocks from the dam top to the depth below seepage is detected. This kind of rehabilitation is attempted in 110m Kakki dam in Kerala, India [30].

8.4.4. Hirakud dam. Hirakud Dam, India, a multipurpose project comprising of a composite dam constructed of earth, masonry and concrete, built across Mahanadi river, was commissioned in the year 1957. The project authorities studied various options such as increasing the height of dam, construction of additional stretch of spillway on the dyke at left /right bank, diminishing the crest level of the spillway, etc. to route the revised flood without endangering the safety of the dam. After analysing various options, and consultation with various authorities, the proposed intervention is to construct an additional length of spillway on the left dyke, spillway with five radial gates having a capacity to release about 3.20 lakh cusecs and other related structures. This construction will pass through and include habitations causing to considerable resettlement impacts necessitating a Resettlement Action Plan based upon an Environmental and Social Management Framework approved by various competent authorities. Such kind of rehabilitation requires extensive planning and execution and challenges are multifaceted [31].
9. Conclusion
Concrete and masonry dams will be subjected to deficiencies and deterioration primarily due to ageing and due to various structural, hydrological and operational aspects besides factors such as revision of guidelines. The reasons for rehabilitations are not typical but vary for each dam. Selection of the most suitable remedial measure is decided by the problem. The necessity for rehabilitation of large dams of these categories is important considering their demand for future benefits without any risk on safety of the stakeholders downstream. The structural, hydrological, operational and management aspects are to be reviewed periodically through comprehensive safety evaluations and based on meticulous analyses and planning the rehabilitation have to be implemented to alleviate the risk that may result in the absence of such intervention.

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