Safety Management of Existing Dams

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ABSTRACT

The consequences of dam failure can be catastrophic. Dams are constructed for various purposes such as hydropower generation, irrigation or municipal water supply, recreational use and storage of mining waste etc. In most cases, it is not only the services provided by the dam that are in jeopardy, due to the failure of the dam, but also endangered are lives, property, the community and its economic well-being and the environment.

Many catastrophic dam failures have occurred around the world and many countries have taken steps to minimize the risks to the community posed by dams by establishing statutory authorities to regulate the safety of dams.

In ensuring the structural safety of a dam; safe operation, proper maintenance, regular surveillance (inspections and monitoring) and the review of safety throughout the life of the dam are as equally important as the assurance of quality in design and construction of the dam. Therefore, it is vital to have in place carefully crafted maintenance, surveillance, safety reviews and operator training programs for existing dams.

The use of recognised standards for design and construction, well managed operation and maintenance procedures, surveillance and safety review programs will minimise the risk of dam failure. Unusual circumstances can result in catastrophic dam failures. Therefore it is important to identify those conditions that could lead to dam failure and develop plans (Dam Safety Emergency Management Plans) to manage those situations should they occur. These plans should stipulate the protocols and procedures to be followed by dam operation personnel (or the dam owner) to respond to and mitigate the emergency conditions at the dam and provide timely warning to appropriate agencies to protect downstream communities if the dam is at risk of failing.

Depending on the number of downstream residents at risk due to the failure of a dam, the agencies responsible for evacuation of downstream communities may need to have up to date evacuation plans in place. Dambreak studies are required to be undertaken by the dam owner to assess the potential dam failure consequences and identify the population at risk due to various dam failure scenarios (sunny day failure, failure under various flood conditions). Inundation maps developed through dambreak studies can be used to develop evacuation plans.

This paper presents a dam safety management framework that enhances the safety of existing dams and protects the safety and welfare of the community from dam failures.

1 INTRODUCTION

Dams are an imperative part of the infrastructure of many nations. They provide immense benefits to the community. Hydropower, irrigation for agriculture, municipal water supply, recreation, flood mitigation and storage of mining waste are some of the major benefits provided by dams and the reservoirs they impound. As a result of population growth and rising demand for energy and water supply, many dams have been built upstream of populated areas. There are about 45,000 large dams (dams higher than 15
metres or dams with a height between 5 and 15 metres and a storage capacity of more than three million cubic metres) in the world and more than two thirds of these dams were built in the last fifty years.

Being a nation hugely reliant on agriculture and hydropower, Sri Lanka has benefited enormously from dams. Sri Lanka has about 320 dams classified as Medium or Large dams. The history of dams in Sri Lanka goes back more than 2500 years. The “Bassawakkulama”, “Tissa Wewa” and “Nuwarawewa” dams in Anuradapura were initially constructed between 500 BC and 100 BC and restored in the 19th century.

Every dam is unique in its design and construction. Performance of these structures under all the design loading conditions cannot be fully tested prior to placing them in operation. Serious structural problems resulting from design shortcomings, construction or material deficiencies or unidentified poor site conditions may not become known for many years. The engineering properties of the foundation or the material used to build the dam can deteriorate over time. Dams require ongoing surveillance, care and maintenance; first to keep them in operational condition, and then to maintain their structural integrity and safety.

Most of the problems that develop in dams can escalate rapidly due to the dynamic nature of water that is impounded by the dam. There are certain structural problems and deteriorations that can lead to serious dam accidents or dam failures. They should be detected as they develop and rectified before they escalate to situations that could threaten the integrity of the dam.

There are numerous instances where regular surveillance (inspections and monitoring), exercising and testing of critical equipment (spillway gates, outlet valves, etc) have detected unusual conditions and adverse behavioural trends that had the potential to threaten the integrity of dams. They include structural or geological problems identified by the routine surveillance activities or mechanical or electrical problems identified through routing maintenance and exercising of the critical equipment. In many instances, early detection of the adverse conditions has enabled:

- implementation of remedial measures to preserve the integrity of the dam or when that was not possible,
- implementation of measures to mitigate consequences of failure of the dam.

The following are some of the instances where regular surveillance has prevented catastrophes:

- **Fontenelle Dam in USA** – In September 1965, the 40 metre high, 1653 metre long earthfill dam built in 1963 experienced a massive seepage that caused a partial collapse of the embankment. Quick actions by the dam operations personnel in lowering the reservoir water level and stabilising the collapsed area by placing rockfill prevented failure of the dam.
- **Zeyzoun Dam in Syria** – The five year old dam failed in June 2002 releasing a 71x10^6 m^3 storage. Early detection of the impending failure allowed evacuation of hundreds of people downstream reducing the loss of life to about 20.
- **Baldwin Hills Dam in Los Angeles** – The 12 year old dam failed in 1963. The failure was caused by piping through the embankment. The caretaker noticed heavy seepage flows only four hours before the failure. Many hundreds of people were evacuated from the downstream areas and only five people died as a result of the dam failure flood.

Furthermore, when the dams are built, they are designed to withstand certain levels of flood and earthquake loadings that are determined based on their individual “Hazard Potential”. They are not expected to be safe under all the extreme flood and earthquake events that could conceivably occur. Extreme floods and earthquakes can threaten the safety of dams.

High standards used in investigation, design, construction, operation, maintenance, safety surveillance (inspection and monitoring), regular safety reviews and remedial works can enhance the safety of dams. Nonetheless, these structures can fail, due to structural deficiencies or under extreme loading conditions, resulting in catastrophic consequences including loss of life. The likelihood of failure of a dam could be
very low but the consequences of failure could be much more significant. A community may take decades to recover from such catastrophes.

Many dams have failed all around the world resulting in catastrophic consequences and in some cases causing the loss of many lives. Every year, we learn of at least one significant dam failure somewhere in the world and many serious incidents or near failures. The following are just a few of the hundreds of significant dam failures that have occurred around the world in the last few decades:

- **Kanthale Dam in Sri Lanka** - 18 metre high embankment dam originally built in the 7th Century and restored in 1875 failed in 1986 killing 129 people (including 59 people missing) due to failure of an outlet structure.
- **Teton Dam in Ohio, USA** - 123 metre high (93 metre high above the river bed), 976 metre long earthfill dam failed during commissioning in 1976 due to piping failure initiated by design and construction deficiencies, killing 11 people.
- **Vaiont Dam in Italy** - 265 metre high 190 metre long concrete arch dam (one of the highest dams in the world) completed in 1961 was overtopped by a wave caused by a massive landslide fell into the reservoir in 1963 claiming the lives of more than 2,500 people (although the dam wall itself did not fail).
- **Banqiao Reservoir Dam in China** - Banqiao Dam was a 118 metre high embankment dam that was built in the early 1950s and failed in August 1975 due to inadequate spillway capacity. Shimantan Reservoir Dam and several smaller dams in Henan Province failed during this extreme storm event. Several thousand people died due to this catastrophic event.
- **Gouhou Dam in Qinghai Province, China** - 71 metre high concrete-faced rockfill dam built in 1988 failed in August 1993 due to internal erosion and piping, killing more than 300 people.

2 **GLOBAL TREND IN DAM SAFETY MANAGEMENT**

An increasing trend in the implementation of various measures to protect the public from consequences of dam failures can be seen around the world. Many countries regard dam safety as a national concern and have enacted legislation to regulate dam safety and established regulatory authorities to develop and implement measures to ensure the safety of dams. These authorities formulate the dam safety management standards for the dams in their jurisdictions and monitor compliance with these standards. The standards normally cover all stages of a dam’s life cycle.

These dam safety regulatory frameworks generally address the following two basic dam safety issues:

- Safety of the dams in their jurisdictions
- Safety of the community downstream of the dam

Some jurisdictions have regulatory authorities exclusively dedicated to dam safety management. There are certain jurisdictions where the regulatory authority deals with dam safety as part of its broader responsibilities in the areas of management of water resources, energy, natural resources etc. Furthermore, there are many international and national non-governmental associations (International Commission on Large Dams, Australian National Committee on Large Dams and New Zealand Society on Large Dams etc) that provide a forum for the exchange of knowledge and experience in dam engineering and develop guidelines for various aspects of dam safety management.

2.1 **Classification of dams**

Many dam safety management authorities worldwide give critical consideration to the “Hazard Potential” in determining the extent of dam safety management requirements for dams. The “Hazard Potential” of a dam is the magnitude of the potential incremental adverse consequences expected in the event of failure of the dam. The consequences include potential incremental loss of life, cost of damage to property, industry and infrastructure, loss of services, social disruption, damage to the environment and the cost of replacement of the dam if the dam is essential to maintain services.
It is extremely difficult to establish a basis for quantitative assessment of the hazard potential mainly because some consequences such as social trauma and personal grief cannot be quantified. The hazard potential assessment is therefore undertaken as a qualitative assessment based on experienced judgement.

A “Hazard Potential Classification System” is used to categorise dams according to the degree of their hazard potential. Various classification systems are used around the world. Australian National Committee on Large Dams (ANCOLD) has a classification system with seven “Hazard Categories” (Extreme, High A, High B, High C, Significant, Low and Very Low). British Columbia Dam Safety Regulation defines a classification system with four categories (Very High, High, Low and Very Low). US Federal Emergency Management Agency uses a classification system that has three categories (High, Significant and Low). Extreme, very high or high categories represent catastrophic consequences whereas very low or low categories represent insignificant consequences. Each classification system has its own criteria for determining the hazard categories. The following Table 2.1.1 shows sample criteria for a four level classification system with High Hazard, Significant Hazard, Low Hazard and Very Low Hazard categories:

<table>
<thead>
<tr>
<th>Population at Risk due to dam failure</th>
<th>Severity of Damage due to dam failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minor</td>
</tr>
<tr>
<td>0</td>
<td>Very Low Hazard Category</td>
</tr>
<tr>
<td>0 to 10</td>
<td>Low Hazard Category</td>
</tr>
<tr>
<td>10 to 100</td>
<td>Significant Hazard Category</td>
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<tr>
<td>&gt;100</td>
<td>High Hazard Category</td>
</tr>
</tbody>
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Development of inundation maps based on a dambreak analysis and survey of dwellings (and other habitable buildings) are required to make a conclusive assessment of consequences of failure of a dam. Detailed dambreak studies are expensive to undertake. The need for undertaking a detailed dambreak study can be assessed by undertaking a simplified dambreak study or by inspecting the downstream areas. However, in some cases the dambreak consequences are so obvious that a reasonable assessment of the consequences can be made by inspecting the downstream areas or using a simplified dambreak study.

The size or type of the dam, the capacity of the storage or the current safety status of the dam is not taken into account when the hazard potential is assessed or the hazard category is determined. A 15m high dam and 100 m high dam could both fall into the same hazard category. For example, the hazard category of the dam which forms the Kandy Lake (in Sri Lanka) could fall within a higher category than that of many larger dams in the country as the Kandy Lake is situated immediately above the commercial business area of Kandy.

Generally the hazard category of the dam is the primary factor that determines the extent of inspection, monitoring, operation, maintenance, emergency management requirements and design criteria for a dam.

3 DAM SAFETY MANAGEMENT PROGRAMS

Dam safety management is basically a two fold task:

I. Preserve the integrity of the dam and maintain it in serviceable condition.
II. Protect the community if the safety of the dam is under threat or if the dam has failed.

A carefully drafted Dam Safety Management Program should be in place to carry out these two tasks at least for all the dams where the failure has the potential to cause loss of life or significant property or environmental damage. The extent of the program and the amount of resources required to implement the program vary from dam to dam depending on the hazard category of the dam, the level of risk at the dam
(the likelihood of a failure occurring), the size and type of the dam. The extent of dam safety surveillance activities increases as the hazard category increases or the safety status weakens.

This paper discusses the dam safety management needs of the dams that have the potential to cause loss of life or catastrophic consequences due to failure of the dam. For the dams that have been classified as having a very low hazard category, a simple safety surveillance program can be implemented in order to ensure continuing safety of the dam.

The following activities, programs and resources need to be in place to satisfy the above mentioned first dam safety management task of preserving the integrity of dams and maintaining them in serviceable condition:

1. A Dam Inspection Program
2. A Dam Monitoring Program
3. A reliable Operation and Maintenance Regime
4. Periodical Safety Reviews
5. Timely implementation of Remedial Works

The above activities can minimise the risk of dam failures. However, unusual circumstances can result in situations that could threaten the integrity of the dam. Urgent actions are required in these situations to prevent or mitigate catastrophic consequences. Preplanning and preparedness are essential to manage these emergencies. Emergency action planning should therefore be incorporated into the dam safety management program. The following two types of plans therefore need to be in place to undertake the second dam safety management task of protecting the community if the safety of the dam is under threat or if the dam has failed:

7. Emergency Management Plan to help the dam operators/owner to manage the situation at the dam and to provide timely warning to the downstream emergency management agencies to implement measures to protect the downstream community
8. Evacuation Plan to help the downstream emergency management agencies in timely evacuation of the affected people.

3.1 Dam Inspection

Regular inspection of a dam by personnel who are capable of identifying abnormalities that could jeopardise the safety of the dam is an important aspect of a dam safety management program. Normally there are four types of inspections.

I. Routine visual inspection by operating personnel: These are the most frequent inspections of a dam. They should be carried out by trained operating personnel who possess knowledge of visual signs of dam safety deficiencies. The frequency of these inspections can be daily to weekly depending on the hazard category of the dam. These inspections are normally undertaken according to a dam specific checklist developed by an experienced dams engineer. Any significant abnormalities noticed by the inspecting personnel (e.g. new cracks, a subsidence in the embankment, etc) are immediately brought to the attention of a dams engineer.

II. Regular visual inspection by a dams engineer: These inspections are undertaken by experienced dams engineers in collaboration with the operating personnel. They should be undertaken at least annually. The following activities should be carried out as part of the inspection:
- Visual inspection of the dam and its appurtenant structures and operating equipment
- Examination of the dam monitoring equipment
- Audit of competency of operating personnel, operation and maintenance (O&M) manuals, O&M records, emergency management plans etc
- Review and evaluation of monitoring results, routine inspection information and other information related to the safety of the dam
• Preparation of a report with recommendations for corrective actions to address the issues identified

III. Comprehensive inspection by specialists: This is a major inspection of a dam and it is undertaken by dams engineers and other relevant specialists (Geologists, Gates & Valve Specialists, etc). The inspection is a part of a detailed review of the performance of the dam with the view to determining whether the dam is considered safe or not. These performance reviews, together with comprehensive inspections, should be undertaken at least five yearly. The following activities should be undertaken during these inspections:
  • Thorough examination of the dam and its appurtenant structures including internal inspection of the outlet structures and equipment
  • Test operation of the critical equipment
  • Inspection of the geology and topography including the reservoir
  • Review of records such as previous inspection and monitoring data analysis reports, maintenance records, special inspection and investigation reports, etc
  • Review of the adequacy of existing inspection and monitoring programs
  • Review of the dam’s hazard category
  • Review of emergency management plans
  • Preparation of a Comprehensive Inspection Report.

The comprehensive inspection report should provide a detailed review of the performance of the dam and contain the following information:
  • Inspection observations
  • Review of operation, maintenance, inspection and monitoring activities
  • Review of the hazard category
  • Review of activities that have occurred since the last comprehensive inspection (special investigations & studies, incidents, modifications to the dam, etc)
  • Review of performance of the dam since the previous inspection
  • Review of the status or progress of any remedial or upgrading works proposed in the previous comprehensive inspection report.
  • A brief review of flood handling capacity and the safety of the dam against the current standards
  • Review of the adequacy of the existing dam safety management program
  • Report findings and recommendations.

IV. Special Inspections: These inspections are undertaken as needed for a particular purpose or following an incident (e.g. earthquake, flood, emergency situation) in order to identify the need for any protective or corrective actions. The inspection may be undertaken by various specialists as required. A report should be prepared documenting the observations, assessment of the situation and recommendations.

3.2 Dam Monitoring

Continuous examination of performance and behavioral trends of the dam is an important activity of an overall safety management program for a dam. This is achieved by monitoring various parameters that can indicate the performance and structural condition of the dam. Various instruments are used to collect the monitoring data. The parameters that could be monitored at a dam include reservoir water level, rainfall, atmospheric temperature, seepage, leakage, analysis of seepage water, pore-water pressure, uplift pressure, ground water levels, internal movements, foundation movements, internal stresses & strains, surface displacement, topographic movements and seismic events.

The parameters that are required to be monitored for a particular dam should be determined by the designer or dam engineers who are undertaking the comprehensive safety review of the dam. The collection of monitoring data should be undertaken by trained personnel. Evaluation and interpretation of monitoring
data should be done by engineers who are familiar with the history of the dam and the criteria used in the
design of the dam.

The frequency of collection of various monitoring data is determined by taking into account the hazard
category of the dam, risks associated with the dam and type and size of the dam.

The parameters such as reservoir water level, rainfall, seepage and leakage are normally monitored on a
daily basis for the dams that have a very high hazard potential.

3.3 Operation and Maintenance

Correct operation and timely maintenance is important in ensuring the ongoing serviceability and safety of
a dam. Improper operation can cause damage to the equipment and dam and pose threat to the downstream
communities. Timely maintenance, regular testing and exercising of equipment will ensure the operational
preparedness of the dam.

Safe operational procedures for both normal and special operational activities should be developed and
documented by the operational staff and dams engineers. These procedures should be regularly tested,
reviewed and updated.

The owners should make sure that the operating staff is competent in the operation of the dam under all
conditions. Training programs can be established to improve the operational skills of the operating staff.

Programs for preventive maintenance should be developed and made available in the O&M Manuals. The
preventive maintenance can be routine (such as lubricating equipment, exercising gates and valves, etc) or
condition based (such as painting, replacement of gate seals etc). The maintenance program should include
activities such as inspections, exercising and testing of various equipment and installations in order to
identify the condition based maintenance needs.

Records of exercising and operation and maintenance of equipment should be kept for verification of
operation and maintenance compliance with O&M Manual requirements and performance evaluation of
various equipment and components in the dam.

O&M Manuals should be available to provide accurate up-to-date operating procedures, maintenance
instructions and schedules for the dam. The instructions in the O&M Manual should enable operators who
are unfamiliar with conditions at the dam to operate the dam during an emergency situation.

3.4 Safety Reviews

The performance of a dam can deteriorate with time due to various reasons such as changes in material
characteristics, construction defects, deterioration of various components and blockage of filters or uplift
pressure relief drains. The field inspections and monitoring activities could also identify structural safety
concerns. The design criteria could change as the engineering knowledge and technology advance and more
data about extreme events is gathered.

Therefore, it is imperative to review the structural, geotechnical, hydrological and hydraulic design aspects
of a dam every 10 to 15 years or if any of the following circumstances arose, in order to ensure that the dam
meets the prevailing safety criteria:

- If any safety deficiency or weakness was identified through the inspection and monitoring
  program or by any other means
- If the accepted design criteria changed
- If the behavior of the dam is not known.

Additional investigations may have to be undertaken to complete the safety review studies.
These safety reviews should be undertaken by experienced dams engineers in collaboration with experienced hydrologists, geologists and other specialists as necessary.

3.5 Remedial Works

Timely remedial measures should be implemented to rectify the safety deficiencies identified through safety reviews and by other means. The remedial measures could either be structural or non-structural. Risk assessment techniques are now being used as part of the decision making process to determine the need for remedial actions or the selection of the remedial option.

3.6 Operator Training

The safety and other objectives of dams cannot be achieved without competent and well trained personnel to undertake operations, maintenance, safety surveillance and emergency planning and management activities. The dam owners or managers should be well aware of the responsibilities relating to dam safety, the hazards posed by the dams and the risks associated with them. Their expertise and awareness can be best achieved through effective dam safety education programs. This education can be delivered through regular involvement of personnel in training courses, seminars and workshops, field exercises and various dam safety management activities. In particular, field staff undertaking operation, maintenance, inspection and monitoring activities should be given adequate training on safe operational procedures, operational risks, environmental issues with regard to operation of the dam, maintenance practices, visual identification of signs of dam safety deficiencies, emergency response procedures, monitoring procedures and dam failure modes.

Dam safety training courses can be tailored to suit the needs of various groups of personnel (managers, operating and maintenance personnel, surveillance staff, dam engineers and other technical staff). The dam owners or managers should ensure adequate training is also provided to the personnel involved in managing the safety of dams.

3.7 Emergency Management Plans

These are dam specific emergency action plans that identify emergency conditions that could lead to dam failures and stipulate emergency measures to prevent such failures, and if that is not possible, to minimize the dam failure consequences. The plan would prompt the owner/operator to provide timely warning to downstream emergency management agencies for implementation of protection measures for the downstream communities if a dam failure or a damaging release of the storage is likely.

These plans are developed by the dam owner and they should exist for the dams that have the potential to cause loss of life in the event of failure of the dam.

Dam failure inundation maps for various possible dam failure scenarios should be developed based on dambreak studies in order to identify the extent and timing of inundation from various potential dam failures. The emergency management plan should be developed in collaboration with all the agencies and individuals who could be involved in implementing the plan.

The plan should essentially have the following information:

- Notification flowcharts to provide timely notification to operating personnel, downstream emergency management agencies or communities.
- Procedures for easy identification, evaluation and classification of emergency conditions
- Inundation maps.

Training programs should be in place to familiarise the users with implementation of the plans. The plan should be tested and updated periodically. Drills simulating emergency conditions can be conducted to familiarise the users and test the plans.
3.8 Evacuation Plans

Evacuation plans are developed by the authorities responsible for evacuation of downstream communities in the event of a dam failure. These plans are developed based on the inundation maps and information provided by the dam owner. These plans should also be tested and updated periodically.

REFERENCES

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Daniel D. Bradlow, Alessandro Palmieri, and Salman M. A. Salman, Regulatory Frameworks for Dam Safety