Lessons Learned from Dam Incidents and Failures

Lessons Learned Identified

Seepage along penetrations through embankment dams should be controlled using a filter diaphragm instead of anti-seep collars.
A concrete encasement or cradle around or under conduit penetrations through earthen embankments allow for better compaction of earthfill.
The first filling of a reservoir should be planned, controlled and monitored.
Uncontrolled vegetation on and around dams hinders effective dam inspection and can lead to serious structural damage, significant deferred maintenance costs and dam failure.
Regular operation, maintenance, and inspection of dams is important to the early detection and prevention of dam failure.
Emergency Action Plans can save lives and must be updated, understood, and practiced regularly to be effective.
Treatment of fractured foundation rock for embankment dams is important to prevent internal erosion of embankment material that is in contact with the foundation.
Stability of the dam foundation and other geologic features must be considered during dam design.
The design engineer(s) should be involved in the construction phase of dam projects.
High and significant hazard embankment dams should have internal filter and seepage collection systems.
External independent peer review of designs and decisions is an effective means of providing quality assurance and reducing the risk associated with design oversights and deficiencies.
Engineers performing dam inspections and assessments should have a sound knowledge of the as-built features and common design practices in use at the time of dam construction to help them identify potential failure modes and other vulnerabilities.
In emergency situations, lowering the reservoir can be an effective means of risk reduction.
Filters and drains for embankment dams must be compatible with adjacent fill or in-situ materials.
Many years of successful dam performance does not guarantee future successful performance.
Safety should not be sacrificed for cost.
Earth/rock cut spillways can fail by erosion and breaching and should be evaluated for integrity during passage of the design flood.
PMF magnitude floods do occur.
High and significant hazard dams should be designed to pass an appropriate design flood. Dams constructed prior to the availability of extreme rainfall data should be assessed to make sure they have adequate spillway capacity.
The use of corrugated metal pipes in embankment dams is discouraged.
Concrete gravity dams should be evaluated to accommodate full uplift.
Pumped storage embankment dams should have an emergency spillway or other redundant features to prevent overfilling and overtopping of the embankment.
All dams need an operable means of drawing down the reservoir.
Warning time and rapid response is critical to saving lives during a dam failure emergency.
Gates and other mechanical systems at dams need to be inspected and maintained.
Dams need to be regulated by state or federal agencies.
Many dam failures are the result of a combination of events and can include human, natural, or structural factors.
Intervention can stop or minimize the consequences of a dam failure. Warning signs should not be ignored.
Dam owners need to address public safety at dams.
Hazardous hydraulic conditions such as hydraulic rollers can occur at dams of all sizes.

The consequences of intentional controlled releases from dams need to be understood and carefully executed.
Dams located in areas of potential seismic activity need to be evaluated for liquefaction, cracking, potential fault offsets, deformations, and settlement due to seismic loads.
Alkali-aggregate reactions (AAR) can cause serious concrete deterioration and other problems at concrete dams.
The hazard classification of a dam can change over time (hazard creep).
Most concrete dam failures are the result of foundation stability problems. Concrete dams founded on bedrock require subsurface investigations and testing of rock properties.
Outlet works and pressurized conduits in embankment dams should be provided with a means for upstream closure.
Dams should be inspected and monitored during and/or after large rainfall, seismic, or other unusual loading events.
Poor compaction, steep rock abutments, and other foundation discontinuities at embankment dams can lead to differential settlement, cracking, and failure by internal erosion.
Dams built from or on loose granular soil can be susceptible to liquefaction of the foundation material.
Settlement of earthfill embankment dams can reduce freeboard and increase the risk for overtopping. New embankment dams should be designed with allowances for settlement.
Discontinuities in grass-lined spillways can accelerate erosion and lead to significant damage or complete breaching of the spillway.
Most dam incidents and failures can be attributed to human factors.
Modifications to spillways can unintentionally decrease their capacity. Any modification to a spillway should be reviewed and approved by a professional engineer.
Geotextiles should not be used as the primary means of filtration in drainage systems for dams.
To the extent practicable, dispersive soils should not be used in the construction of embankment dams.
For new dams, the as-built conditions of critical elements should be verified through direct observation and/or testing. This is particularly important for critical elements that are constructed "in the blind."
For high and significant hazard dams, elements that are critical for the safe operation of the dam should be designed using the "belts and suspenders" approach.
Internal erosion can occur at relatively low hydraulic gradients.
Internal erosion can take decades to progress.
Structural underdrains can lead to internal erosion under or along stilling basins and conduits.
Non-plastic soils are far more likely than soils with some plasticity to experience internal erosion.
Cutoff walls can concentrate gradients and seepage flows.
Karstic foundations are difficult to treat and can cause internal erosion issues.
Concrete dams on rock foundations are not immune to failure during flood overtopping.
During floods that greatly exceed the design flood, spillway failure (due to exceedance of the spillway capacity) may be a more critical potential failure mode than dam overtopping.
Hard rock spillway channels and hard rock concrete dam foundations may erode under the right flow conditions combined with unfavorable joint orientations and other joint characteristics.
Dams may overtop for floods more frequent than the design flood if the spillway capacity is reduced (due to debris plugging or gate malfunction) or if a gated spillway is not operated as assumed in design studies.
Dam operators may operate a gated spillway at release levels less than those specified in the SOP if there is the potential for downstream consequences.
Spillway gates should be tested to the maximum extent possible on a regular basis to verify the performance of the electrical/mechanical system and to ensure that the gates can travel freely without binding or being restricted.
Dam performance and conveyance capacity should be re-assessed following significant changes in land use within the contributing watershed.
In order to reduce uplift pressures in sand aquifers overlain by clay layers in earthfill dams, granular filters installed directly on the underlying foundation can be an effective solution.

Maintaining dam records such as as-built plans, construction data, reports, diaries, previous studies, inspections, instrument readings, maintenance records, etc. is important.
Some dams may not have included clean out of the stream channel under the embankment. This can be a source of uncontrolled seepage under the embankment.
Raising the normal pool or crest of an existing dam requires evaluation of existing and new potential failure modes as well as the stability of the dam for the new loading condition. Dam modifications need to be designed by a professional engineer.
Prior to cement grouting of rock zones that are highly permeable and have high piezometric gradients, it is important, when possible, to reduce the flow and the piezometric gradient in the area where the grout is to be injected.
Aeration of the underside of the nappe is often needed to mitigate vibrations in spillways.
Emergency Action Plans for dams should include a list of available resources available (materials, equipment, contractors, etc.) to help respond to emergencies.
At dams where failure or near failure has occurred, proper mitigation and/or rehabilitation should be performed to ensure that similar events cannot recur.
Construction of a cutoff in alluvial foundation materials if often needed to prevent potential internal erosion.
Pressurized pipes in embankment dams require special design features.
Safe access to high and significant hazard dams at all times is important.
The foundations for an arch dam should be properly treated by replacement of poor rock with concrete, grouting, and drainage.
Because of their need to transfer load to surrounding rock, the abutments and foundations of arch dams require special geologic exploration, evaluation and treatment.
Outlet conduits at dams need to be inspected regularly to confirm their structural integrity and conveyance capacity.
Dam safety regulatory agencies should have an in-house Emergency Action Plan for responding to emergencies.
It is prudent to provide very high discharge capacity for seepage collection and control systems for dams constructed on glacial foundations.
In order to control seepage in glacial foundations, sand filters and other drainage zones should be limited to minimum dimensions that can be reliably constructed, thereby providing as little resistance to concentrated seepage flows as practical.
A properly designed and executed foundation grouting program can provide an effective seepage cutoff.
Siphons can be an effective method to lower reservoir pool levels during emergencies when outlet works are inoperable, undersized, or missing.
Outlet works conduits with joints in embankment dams should be watertight to prevent internal erosion of the embankment.
Conducting potential failure modes analyses (PFMAs) and periodic assessments of high and significant hazard dams are effective methods that help keep dams safe.
Coordination between geologists, designers, and contractors is important.
Foundation approval should be documented by designers and geologists.
Effective communication with emergency responders is important when responding to a dam emergency.
Moisture content and compaction of embankment fill material must be carefully monitored for acceptance during construction.
Under certain conditions at a dam site, flows exiting spillways can double back and erode and breach the dam embankment. Dam designers and inspectors need to be aware of this potential failure mode.
Landslides around the rim of a reservoir can cause dam overtopping. The stability of the hillsides around the rim of the reservoir as well as the impact of potential slope failures should be evaluated.
Uncontrolled animal activity can contribute to or result in a dam failure.
Dams have confined spaces that need to be marked and only entered when it is determined to be safe and the entry is in compliance with confined space entry and monitoring procedures.
Drainage conduits for dams should be designed with cleanouts to accommodate future cleaning and inspection.

Trash racks need to be appropriately sized and cleared after large flow events.
Peer review and collaboration during dam design can prevent design-attributed failures.
A well maintained grass cover can prevent damage and breaching of embankment dams during minor overtopping events.
Concrete dams should be evaluated for and protected from foundation and/or abutment scour.
Special attention must be given to the compaction of earth fill around discontinuities such as along outlet structures and other penetrations through embankment dams.
Rapid filling of clay dams after long dry periods should be avoided.
The presence of weak zones in natural foundation materials must be evaluated in design.
Brittle materials, such as asphalt and Portland cement concrete, should not be used as reservoir liners without high capacity filtered underdrains.
Zones of permeable soil, such as old riverbed deposits in dam foundations, should be addressed.
Seemingly small changes to dam details can cause failure of a dam.
Proper management of runoff and pool water is essential to the safe operation of tailings dams.
Grouting of earth fill or overburden material should not be used as a long-term/permanent solution to prevent internal erosion.
Dams constructed by hydraulic fill methods can be susceptible to liquefaction during seismic events.
Flooding resulting from a dam failure may extend further than noted in inundation maps.
Dam repairs should be executed promptly.
Spillways should be designed to prevent clogging by debris.
Excessive headloss in inlet piping can be a failure mode.
Fault activation and subsequent dam failure can be caused by high-pressure injection of fluid into subsidence-stressed subsurfaces.
Grout curtains in a formation where potential seepage paths (joints, fractures, etc.) are filled with either erodible or soluble materials are not permanent and may require periodic maintenance grouting to remain effective.
Conventional instrumentation may provide early detection of conditions within a dam that could lead to failure.
Conventional instrumentation can induce or accelerate internal erosion.
Compatibility of materials to prevent piping of materials through embankment and foundation materials needs to be considered. Special consideration is necessary for broadly graded and variable soils deposits (glacial, alluvial, and colluvial).
The benefits of EAP exercises are best realized when both dam owners and emergency responders are involved so that weaknesses in protocol procedures and duty assignments can be exposed and corrected before a real emergency occurs.
Critical intervention/action by personnel during a crisis can be precluded by: (1)Power failures preventing use of key equipment; (2)Site inaccessibility due to flooding or road damage; (3)Required travel time; (4)Limited staffing
Flood control dams may not provide an opportunity to observe developing seepage and piping.
Severe piping of embankment materials can occur through a dam into the abutments or its foundation without any deficiencies being observed by dam inspection.
Construction inspection is critical in assuring proper construction techniques and construction in conformance with approved plans and specifications.
Current state-of-the-art two-dimensional modeling combined with LiDAR terrain data may identify areas of inundation for inclusion in the inundation mapping not identified using one-dimensional modeling.
Subsurface inspection of the downstream toe area of run-of-river dams or any spillway structure that is normally inundated by tailwater should be conducted periodically to detect scour and possible undermining of the dam or spillway structure.

An emergency alarm/warning system can be an effective means of providing warning to downstream residents located in close proximity to a dam where the warning time is short.
Foundation and formed drains for concrete dams should be inspected regularly and their performance verified by drain flows and uplift pressure measurements. When drains begin to plug and performance is reduced, a cleaning program should be initiated.
Lime treatment can be used to stabilize dispersive soils used to construct embankment dams.
Principal spillways should be designed to convey high frequency floods without incurring significant erosion damage.
Dynamic compaction can be an effective method to correct seismic deficiencies due to liquefiable embankment materials in earthfill dams.
Emergency design and construction of dam modifications requires proactive involvement between the owner, engineer, regulatory agencies, and the contractor to achieve the most effective combination of constructability, conservative design, and flexibility.
Stress distribution in an arch dam is critically influenced by excessive deformation of the foundations.
Extensive and progressive cracking can seriously impair the safety and durability of a thin arch dam.
In order to reduce tensile stresses in thin arches, the structure should be thickened toward the abutments and river bed.
Grouted interlocking keys are an effective means to construct contraction joints in arch dams.
For new dams, weak features in rock foundations can be mitigated using concrete shear keys and dental concrete.
Where tectonic conditions are similar to those of the Los Angeles region, vertical seismic accelerations can be as high as the horizontal accelerations.
There is magnification of seismic accelerations not only in the upper parts of a concrete dam but also along its abutments.
Vertical interlocking keys in the transverse contraction joints are highly effective in maintaining stability of individual blocks of an arch dam during an earthquake when the reservoir is partially full.
When possible, emergency response should be coordinated with appropriate environmental agencies.
For dam safety regulatory programs, it is important to have a reserve source of funding identified for responding to an emergency.
Installation of an under-slab drainage system can help avoid detrimental frost action while providing a method for monitoring seepage quantities over time.
For dam failures that occur as the result of an earthquake, the failure mode is often attributed to deep seated shearing where the embankment behaves as blocks governed by inertial forces and the undrained strength characteristics of the material.
Injecting air into flow discontinuities caused by small surface discontinuities and changes in high velocity flow direction can prevent cavitation.
Moments and stresses caused by friction within the trunnion pin connection must be considered in the structural design and maintenance of radial gates. Trunnion pin connections must also be lubricated and maintained in accordance with design assumptions.
Dam instrumentation can provide early detection of a dam safety problem and can provide an opportunity for intervention.
Dam systems that rely on automated computerized systems or electrical power to operate require redundancy.
Supporting a dam on piles makes it more vulnerable to foundation erosion and piping.
Poor design and construction practices increase the probability of a dam failure.
Sound engineering is required to build a safe dam.
The mortar and masonry used in masonry dams must be strong and durable.
Static equilibrium, including uplift pressures, must be considered during all phases of construction and service.
Reservoir sedimentation can increase destabilizing forces acting on a dam and have other detrimental effects that could contribute to a dam failure.

Loose rockfill should not be used as structural support in locations where it can be easily eroded.
Gravity dams on soil foundations require special features to address potential erosion of the foundation.
Failure of upstream reservoirs should be considered in the design of closely spaced dams.
Differences in the stiffness of structural materials can lead to unforeseen stress concentrations.
Unique force systems must be anticipated when designing foundations on rock having complex systems of faults and joints.
Delays during dam construction can expose a dam to higher risk of failure.
Reservoir impoundments can reduce the stability of natural slopes.
Reduction in minor principal stresses due to drying or differential settlement can lead to hydraulic fracturing and piping failure in embankment dams.
Erosion through a breach in erodible fill cannot be controlled.
Design features that rely on specific operating procedures need to be documented and clearly communicated.
Dam failure by acts of terror should be considered as potential failure modes.
Special care is needed in placing embankment materials in order to prevent preferential seepage paths due to material variability, segregation and partial fill surfaces.
Proper development of site-specific loading diagrams and related assumptions are an important aspect for any dam design. Key assumptions include selection of dam and foundation material properties that are defensible.
Due to inherent uncertainties relating to both design and construction, appropriate factors of safety need to be applied.
The value of surveillance plans is best realized if the owner's personnel are adequately trained in the various warning signs that indicate the possibility of changed and actionable conditions.
Modern computers and software allow engineers to reasonably determine the potential consequences of dam failure. This has helped heighten the awareness of potential dangers as well as better equip stakeholders in emergency preparedness and response.
An important benefit of active involvement in professional societies is their forum for the exchange of information related to new technology as well as to practices which should be avoided.
Remote sensing/controls should have redundancy, and preferably via a system of a separate nature, such as visual (camera) reconnaissance to confirm reported conditions.
Longwall mining located well beyond the current accepted cone of influence may cause severe impacts on dam foundations and structures.
Crownvetch is not an appropriate vegetative cover for dam surfaces as it may hinder inspections and observations of developing problems.
Low-level outlets for normally dry flood control/stormwater dams must be designed to prevent blockage by beavers in regions where they reside.
Improperly designed or anchored spillway slabs may fail long before a spillway discharges at its designed maximum capacity.
Historic installations of copper waterstop may fail due to corrosion from acid rain or other influences on the chemical composition of runoff.
Quality control of waterstop installations is critical to assure adequate embedment of waterstop materials into the concrete on either side of joints.
A very well-maintained dam is not a guarantee against failure when a dam and its design is dated and does not meet current design standards.
Fish containment structures must be located and designed such that they function properly in extreme runoff events without limiting the outflow capacity of the dam's spillway.
The design life of key components of a dam (e.g. outlet works) may be much shorter than that of the dam structure; therefore, major maintenance or replacement of such components may be required on a shorter time interval.
Drainage conduits in embankment dams should be video inspected using a pipe camera after they have been installed and before construction work is completed.