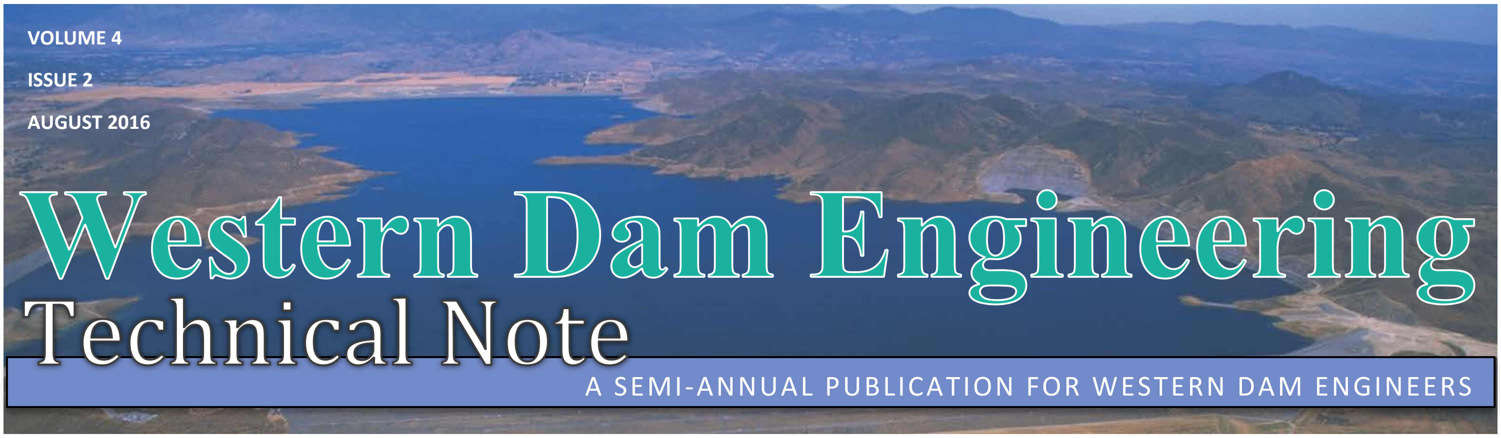

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Western Dam Engineering
Technical Note

A SEMI-ANNUAL PUBLICATION FOR WESTERN DAM ENGINEERS

In this issue of the ***Western Dam Engineering Technical Note***, we present articles on **risks of aging dams**, **upgrading dams to address deficiencies in passing flood flows**, and **internal erosion mechanics**. This semi-annual newsletter is meant as an educational resource for civil engineers who practice primarily in rural areas of the western United States. This publication focuses on technical articles specific to the design, inspection, safety, and construction of small to medium sized dams. It provides general information. The reader is encouraged to use the references cited and engage other technical experts as appropriate.

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GOOD TO KNOW

FEMA Training Aids for Dam Safety (TADS): A Self-Instructional Study Course in Dam Safety Practices

ASDSO NATIONAL DAM SAFETY CONFERENCE, *Sept 11-15, Philadelphia, PA*

Upcoming ASDSO Webinar Dam Safety Training:

- **Hydrologic Hazards - Estimating Probabilities of Extreme Floods** *John F. England, Jr. October 11, 2016*
- **Intro to Tailings Dam and Coal Ash Impoundment Design, Construction and Monitoring** *by Dick Davidson, PE (AECOM); November 8, 2016*
- **Introduction to Dam Decommissioning** *by Paul Schweiger, PE; December 13, 2016*

Upcoming ASDSO Classroom Technical Seminars

- **Inspection and Assessment of Dams**, *White Plains, NY October 11-13, 2016.*

ASDSO Training Website Link

In this Issue

Dam, You're Getting Old! – Understanding and Managing the Risks of Aging Dams

Introduction

Dams are a vital part of our Nation's infrastructure, providing tremendous economic, environmental, and social benefits, including hydroelectric power, water supply for drinking and irrigation, flood control, wildlife habitat, recreation, and navigation. The benefits of dams, however, are countered by the risks they can present. In the event of a dam failure, the potential energy of the water stored behind even a small dam is capable of causing loss of life, significant property damage, and an extended period of loss of the services dams provide [1]. Historically, some of the largest disasters in the United States have resulted from dam failures.

The fact that a dam has successfully served its purpose for decades, or perhaps over a century, is not itself a positive indication for future performance. Dams are long-term structures and need to withstand extreme events. Because so many of a dam's potential detriments caused by aging are internal and difficult to directly see, understanding aging effects and ways to monitor, detect, and manage these developing deficiencies is important to maintaining adequate dam safety.

How old are our dams?

At a current average age of 52 years, most dams in the United States are older than the median age of the U.S. population (38.6 years). The twentieth century was a golden era of dam building in the U.S., reaching its climax in the years following World War II. Dam building began to decline in the 1970s due to the increasing cost associated with new regulations governing dam building coupled with a decreasing demand. Figure 1 presents the construction era of dams within the western states of the U.S. (AZ, CO, ID, MT, NV, NM, UT, WY). In the western U.S. alone, there are more than 1,000 dams over 100 years old.

Older dams were built with minimal design using manual equipment. These dams may have been built in the middle of nowhere but in many cases are high hazard dams in the middle of a residential area now.

What is their condition?

In its most recent Report Card for America's Infrastructure, the American Society of Civil Engineers gave the condition of America's dams a "D" defined as "Poor: At Risk."[2] This is due in part to the growing number of dams needing repair due to the effects of their age, the increasing size of the population protected by dams, and the limited funding available to address deficiencies.

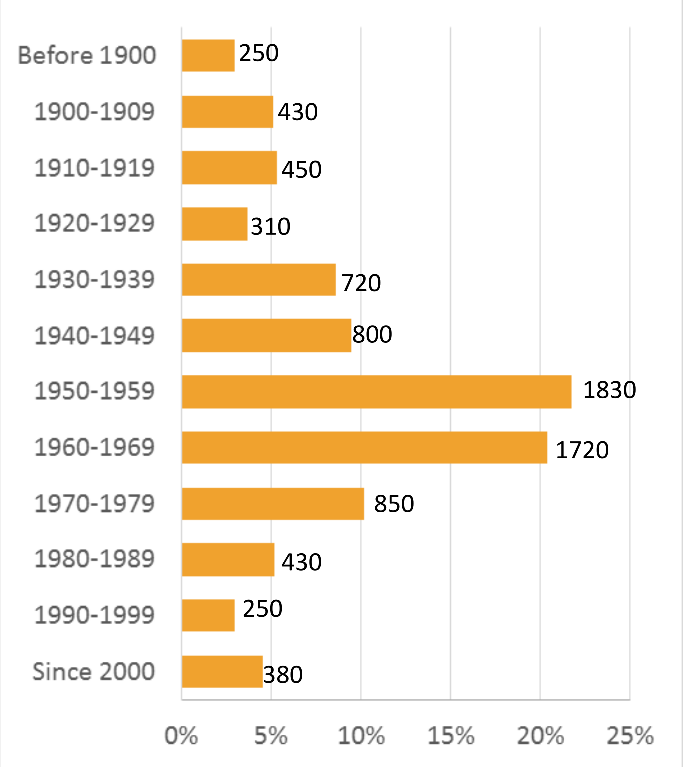

Figure 1. Construction Year (Age) of Dams in the Western U. S. as of 2013 [3]

Why do we care?

The age of a dam has a significant influence on both its integrity and its potential to impose adverse impacts. These impacts include costly repairs to property, financial restitution and fines, loss of intended purpose of the dam, environmental impacts, and potential loss of life. Physical aging processes influence the integrity and longevity of dam structures. Understanding these aging processes is the key to understanding why the thought that "this dam has been here forever and works fine" denotes a false sense of security.

The terms "**Safety**" and "**Risk**" are a function of both the likelihood of the structure to fail, and the resulting consequences (economic, environmental, or loss of life) of the failure. Therefore, dam deterioration that occurs over time, coupled with the increasing development downstream of dams, results in increased risk. This article discusses these time-related phenomena, how they influence the risk dams pose, and the path forward for owners and engineers to maintain safe and reliable structures.

How a Dam's Age Influences Risk

Deterioration

The structural integrity and operational effectiveness of dams often deteriorate with age. Deterioration of dam structures refers to time-related changes in the properties of the materials of which the structure and its foundation are composed. The International Commission on Large Dams (ICOLD), Committee on Dam Ageing, studied the various aging phenomena of concrete and embankment dams and appurtenant works. The committee identified features of deteriorated structures and the processes of deterioration. Methods by which the deterioration may be controlled and perhaps prevented were also identified. These findings were later presented in a white paper published by the United States Society on Dams (USSD) [4]: THE AGING OF EMBANKMENT DAMS. The highlights from this study are summarized at a high level here. The reader is encouraged to read the referenced paper for more details.

Foundation: The causes of deterioration of the dam foundation were identified as:

- Deformation leading to cracking
- Internal erosion (see Figure 2)
- Loss of strength or increase in the permeability due to slaking, dispersion, solutioning, and thermal and chemical processes

Embankment: The causes of deterioration in the dam body were identified as:

- Deformation and settlement leading to embankment cracking or loss of freeboard
- Loss of strength due to improperly compacted fill or cycles of wetting and drying.
- Long-term elevation of pore pressure due to cracking and seepage
- Internal erosion (see Figure 2)
- Surface erosion

Miscellaneous: Other causes of deterioration of dams were identified as:

- Deterioration of conduits due to freeze/thaw, corrosion, or long-term settlement induced cracking (see Figure 3)
- Clogging of internal drainage systems
- Seepage through concrete faced rockfill dams
- Loss of bond between concrete structures and embankment
- Deterioration and/or clogging of geosynthetic material
- Deterioration of asphalt facing
- Deterioration of soil-cement or RCC armoring
- Vegetation and animal activity

All of these can lead to dam safety incidents and failures after years or even decades of successful performance, as presented in Figure 2 and Table 1. The Bureau of Reclamation studied the ages of dams at the time of internal erosion incidents within their inventory of dams. It found about one-third of the incidents occurred within the first five years of operation. However, incidents continue to occur beyond 20 years, with no dramatic decline in rate of incidents after 20 years.

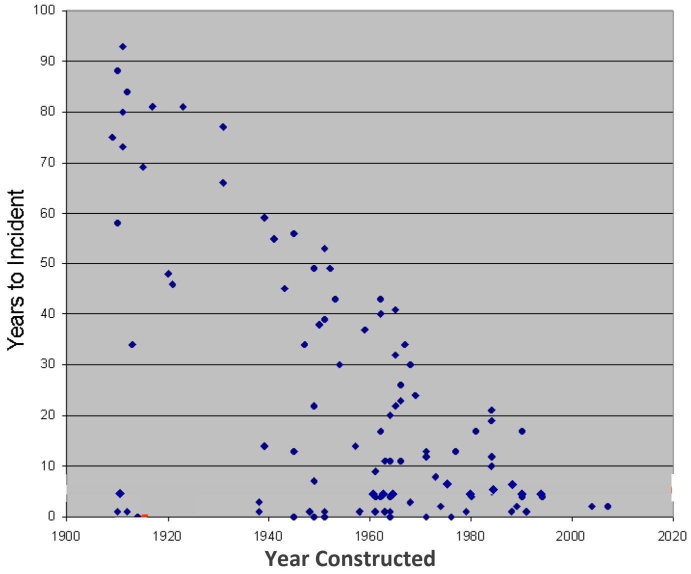

Figure 2. Internal Erosion Incident Timeframe [Adapted from [5]]

Table 1. Age of Dam at Incident [Adapted from [6]]

Dam Age at Incident	No. of Internal Erosion Incidents
≤ 5 years	36
6-15 years	17
16–25 years	10
26-35 years	7
36-45 years	8
46-55 years	5
56-65 years	4
66-75 years	4
76-85 years	5
> 85 years	2
Total	98

Several dam incident and dam failure case histories have been associated with old, deteriorating conduits. Metal conduits, such as corrugated metal pipe (CMP), have a limited life span and are prone to long-term deterioration. Concrete conduits may have a longer life, but also are prone to aging effects such as freeze/thaw deterioration, scour, cracking, reinforcement corrosion, settlement, and deterioration of water stops. Figure 3 shows an example of dam failure after 40 years of operation.

Figure 3. (a) Corrosion of a 40-year-old outlet pipe and (b) its effects.

Outdated Construction Techniques and Materials

Nearly 7,000 U.S. dams are more than 100 years old. Most older dams were built with the best construction and engineering standards available at that time, but much has been learned since then. Technical advances in construction practices specific to dams have resulted in modern structures that are more robust and resilient than their older relatives, and able to better withstand a wide range of loading conditions. Dam failures throughout history were the driving force behind most of the technical advances, but thousands of existing dams—those that haven't failed yet—were constructed using outdated and inferior construction techniques. This may increase the potential for deterioration and long-term performance issues. This section presents a brief list of some of the key advances in construction practice within the twentieth century.

Soil Compaction

Although sheepsfoot rollers were first invented around 1900, they weren't widely used to compact earthfill dams until the 1920s. [7] The sheepsfoot roller's narrow spikes induce a kneading compaction, which is critical for densifying clayey soils. Self-powered scrapers and compactors were not widespread until the 1930s. Advancements in mechanical compaction improved the in-place density of earthfills, which has in turn improved the soil's engineering parameters such as permeability, strength, and resistance to surface or internal erosion and limits settlement.

Hydraulic Fill Placement

The hydraulic fill method is a placement technique that was often used in dam construction prior to about 1970. Hydraulic fill materials are transported suspended in water to the embankment where they are placed by sedimentation. Velocity control is used to control the selected deposition of the material. The coarser particles of the slurry settle out along the outer embankment shells, while the finer particles flow toward the center to become the dam core. However, this practice was largely discontinued after some notable failures of hydraulic fill dams (e.g., Fort Peck Dam, Calaveras Dam, and Lower San Fernando Dam). Although those dams failed in the early stages of operation, there are numerous existing dams that were constructed using this technique that have developed long-term performance issues associated with seepage, settlement, and arching. This placement method is no longer used due to the lack of compaction and difficulty of quality control. The hydraulic fill method often produced stratified, uncompacted, cohesionless fill that would not adequately relieve pore pressure. This can lead to structure instability in undrained loading conditions (earthquake, end-of-construction, flood) due to the reduced material strength. In addition, the large degree of settlement of hydraulic fills as they slowly drain eventually develops arching in the core and prevents its full consolidation.

Miscellaneous

Other advances in materials, equipment, and methods continued to improve the quality of dam construction throughout the twentieth century. These include introducing air entraining agents around 1930 to improve concrete's resistance to freeze/thaw damage and corrosion resistant coatings and materials for metal appurtenances.

Changes in Flood and Earthquake Load Predictions

In addition to static, normal loads, most dams should be designed for unusual and even extreme loading conditions, including those that exceed the historical record of occurrence at the site. Predicting loads induced by these rare events is an exercise centered equally on statistics and engineering. As time passes, the size of the available database increases, which may alter the statistical outcome and at the same time advance the engineering understanding of these phenomena. As a result, predicting rare flood and earthquake loads is an ever-evolving process.

Flood Loading

Dam flood loading is influenced by the hydrologic characteristics of the watershed as well as local and regional meteorological characteristics and processes. Significant advancements in the understanding of these data and processes have resulted in larger, more refined data sets. With these data collection advancements, more precise modeling has been undertaken. These changes in modeling capability support the finding that older dams are not adequately designed for recently predicted floods.

Figure 4. Overtopping of Earth Dam during a Rare Flood Event

Earthquake Loading

Scientists' and engineers' knowledge of earthquake processes and their characteristics, such as ground motions, has increased in parallel with the increase in records of earthquake occurrence. Earthquake databases have significantly improved over the past 50 years, and now represent a more complete distribution of earthquake processes and their characteristics. The increase in the number of seismic recording instruments available to record earthquakes has grown as well. The increase in the number of reliable recording instruments along with the number of events recorded over the last 50 years have provided an enhanced database in which to study earthquake characteristics, improve statistical methods to develop ground motion relationships, and quantify the uncertainty associated with the predictions.

Revised Dam Design Guidelines and Practice

Most older dams were built with the best construction and engineering standards available at that time, but much has been learned since then. The greatest advance in dam safety practice for earth dams is the implementation of engineered filters. Engineered filters, for all practical purposes, were not implemented in dam design until about the 1980s. Most dams constructed before this era likely do not meet modern filter design criteria to protect against internal erosion.

Failure due to lack of filters can take days or years and problems can develop in older dams despite years of good performance. Modern practice and guidelines dictate the use of zoned embankments that include, at a minimum, engineered filters downstream of earth cores and around conduit penetrations and toe drains.

Figure 5. The Result of an Unfiltered Penetration through an Earth Dam in Wyoming

Hazard Creep

The U.S. Census Bureau maintains a POPULATION CLOCK that ticks off a current average net gain of one person every 12 seconds in the U.S. This rate of population gain affects the role of dams in our nation. Land development reduces water infiltration and thus increases runoff and associated flooding. This in turn increases the need for flood control structures. The increase in population also increases the demand for renewable power and recreational sites, both of which are provided by dams.

This population growth will likely move development further into the unpopulated areas below aging dams, increasing the population at risk and reclassifying many low or significant hazard dams as high hazard. This change in hazard classification, or hazard creep, brings owners of dams that were originally constructed as low hazard, costly new challenges to modify the existing structures to meet stricter criteria. There are limited means for owners to be notified and participate in the decision to develop downstream of their dams. Once the development and hazard classification upgrade occurs, the owner is responsible to upgrade the dam for larger flood and seismic loads.

See the related article in this issue for a discussion of hazard creep effects on hydrologic design criteria and methods of managing the hydrologic deficiencies of aging dams.

Managing Effects of Aging Dams

Dams are expensive to build and to fix. According to the Association of State Dam Safety Officials (ASDSO), it would cost over $50 billion to rehabilitate all of the aging dams in the country [8]. So how do owners, engineers, and regulators manage and prioritize the effects of aging on dams?

Monitoring

Monitoring programs can significantly reduce the risk of a dam failure by identifying deterioration in the early stages, giving the owner the opportunity to repair or remediate the problem and avoid severe consequences. Direct evaluation of the effects of aging is possible by monitoring changes in structural properties and physical features. Indirect evaluation results from monitoring the response of the dam to various loading conditions. The following are just a few of the key review and monitoring activities to help evaluate potential effects of aging.

Dam Safety Visual Inspections: Regular inspection of the dam is the most effective means of risk management, as it may identify potential problems before they become a dam safety issue. Inspections should include a review of the embankment (potential changes in grade, surface erosion, seepage, vegetation, animal activity), and all of the appurtenant structures. Inspections should focus on *changing* conditions that may be an indication of deterioration or other internal mechanisms that are not directly visible. The importance of effective dam inspections warrants its own article. See our previous article, DAM SAFETY INSPECTIONS...A CLOSER LOOK.

Design Reviews: Dam safety reviews should be performed by an engineer experienced in dam design and include a review of existing data including analyses, drawings, specifications and construction photos. Although for older dams, much of this information is limited, there are usually a handful of documents including previous inspection reports that can shed light on potential problems and improve the inspection process.

Instrumentation Monitoring: Piezometers: Monitoring pore pressures within the dam and foundation can provide useful information about potential changes in stress, development of cracks and internal erosion, and potential changes in uplift pressures. Surface Survey Monuments**:** Monitoring monuments along the crest of the dam can provide useful information about settlement of the dam or foundation and the development of slope movement over time. Modern GPS receivers make regular monitoring of surface movement less expensive and thus feasible for virtually any dam owner.

Conduit Inspections: Remote conduit inspections can detect deterioration of the pipe and joints that may eventually lead to erosion of embankment material through the conduit. While all pipe has a finite life span, metal pipe and especially CMP has an even shorter lifespan, especially when placed in chemically reactive soils. The condition of the interior of a conduit is best inspected by directly viewing it. However, it may be possible to indirectly determine the trend of a pipe's deterioration through regular chemical analysis of the outflow through the pipe.

Maintenance

Proactive maintenance of changing conditions observed through regular inspections can arrest several of the long-term deterioration processes. It is much less expensive to periodically address developing issues before they become a major incident. Periodic maintenance may include:

- Backfilling animal burrows and root holes
- Maintaining uniform crest elevations through grading and fill placement
- Managing vegetation, especially large, woody vegetation both on the embankment and within earthcut spillways
- Exercising gates and valves
- Performing maintenance on instrumentation
- Clearing debris that may block flood passage

Risk-Informed Decision Making

Because of the high cost of fixing or rebuilding dams, many owners are using risk analysis to prioritize what to fix first. Risk analysis is a systematic approach to estimating the likelihood of various failure modes progressing to a dam breach and coupling that likelihood with the consequences of the breach. Through this process, an owner, or regulator, can compare various deficiencies of a single dam, as well as various levels of risk posed across a portfolio of dams.

Risk analysis begins with brainstorming all of the ways in which the dam could potentially fail—known as Potential Failure Modes (PFMs). The PFMs are then evaluated for the factors that influence the likelihood that the PFM will occur. These factors may include the likely loading the dam may experience, physical attributes of the dam and its foundation, operating procedures, past performance, and ability to detect a developing PFM and intervene before its full progression. Based on these factors, the PFMs can then be ranked or categorized to allow focus on the PFMs of most significance. Formal risk analyses have been used by the Bureau of Reclamation in the U.S. since the mid-1990s; and the risk analysis process continues to expand to other federal and state dam safety agencies, as well as private dam owners and engineers.

Risk-informed decision making is a shift in process, and mindset, from a strictly "standards-based" or "criteria-based" process. In the standards-based process, dams are evaluated in regard to whether they meet minimum factors of safety or modern design criteria. All dam safety agencies and engineers still use this process. However, because so many aging dams do not meet today's standards, it can be overwhelming to determine what is most important to fix. Risk analysis is a tool more and more dam safety engineers, owners, and regulators are using to supplement the standards-based requirements to accomplish the following objectives:

- Identify potential deficiencies of dams and appurtenant structures
- Prioritize a portfolio of dams or a suite of deficiencies at a given dam to decide which are the most important to fix
- Understand the urgency of deficiencies
- Identify effective risk reduction actions
- Evaluate the effectiveness of rehabilitation alternatives

Risk-based decision making does not replace modern standards-based criteria, but provides a means to manage its implementation to the large number of older, aging dams that do not meet modern standards. For dams that do not meet established criteria or standards, most dam safety agencies are beginning to allow the use of risk analysis to strategize a long-term plan to prioritize repairs. However, depending on the level of urgency of the identified deficiencies, short-term risk reduction measures, such as operating at a lowered pool or more frequent inspections, may be required until the deficiencies of highest significance are addressed. Risk analysis is a large topic beyond the scope of this article. Look for future articles on the methodology and use of risk-informed decision making.

The Role of Dam Safety Organizations

Both governmental and non-governmental dam safety organizations provide resources to dam owners and engineers to assist in dealing with the repair and maintenance of aging dams. Most federal dam safety agencies and some states have developed technical resources and guidance documents. Most of these resources and guidelines are available to the public. Engineers and owners can find links through the Technical Resources, Federal Agency, and State Dam Safety Program pages of the ASDSO website. ASDSO also has technical and educational resources specifically for dam owners on the Dam Owner website at www.damowner.org. The United States Society on Dams website has links to white papers on technical subjects and technical publications for sale.

Non-governmental organizations also advocate for funding for dam safety regulatory programs to provide inspections of aging dams and also for grant and loan programs for owners to fund the repair and rehabilitation of aging dams.

Conclusion

Dams that were constructed decades ago have become part of our modern landscape. Some are so small, perhaps with no pool behind them, that the communities that have developed downstream may not even be aware the dams exist—until a flood occurs. When it does, the dam is expected to stand strong and withstand a force of nature that it has never before experienced. In the meantime, the structure may have deteriorated due to the inevitable effects of aging.

The best way to manage the potential risks of aging dams is being aware, attentive, proactive, and knowledgeable. Be aware of the ways dams can change over time and the potential consequences of deterioration of the dam. Be attentive during inspections to detect changing conditions that may provide an early indication of a developing dam safety condition. Perform proactive maintenance to improve the longevity of the structure and limit costly repairs associated with adverse conditions that are allowed to progress. Be knowledgeable in understanding the relative urgency of suspected deficiencies such that the most severe conditions are addressed with appropriate timeliness. With proper vigilance, maintenance, and perhaps some justified upgrades, dams can continue to perform long in the future as well as they did when they were first constructed.

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Retrofitting Old Dams to Address New Hydrologic Inadequacies

Introduction

At the time when dams are designed and constructed they must meet certain hydrologic requirements to ensure their proper operation and safety. However, these requirements can change over the life of a dam, which can impact a dam's compliance with regulatory agencies. The most prominent of these hydrologic requirements is the inflow design flood (IDF), which is the minimum flood event that must be safely discharged through the dam. While IDF requirements vary between regulatory agencies, they are generally based on potential downstream consequences resulting from a dam failure or flood outflow event.

So why do these hydrologic requirements change over time? There can be several reasons, but some of the primary reasons include advancements in knowledge and understanding leading to updates associated with:

1) Hydrologic analyses (precipitation and runoff)
2) Regulatory agency requirements
3) Hazard classifications

These are currently considered the most influential factors driving change in hydrologic requirements for dams and are further discussed in subsequent sections below. However, climate change shouldn't be ignored and is another factor becoming more influential in hydrologic requirements for dams. With the potential to increase the frequency of extreme storm events, climate change will likely continue to become more pertinent and prominent in the future and initiate updates to hydrologic data and regulatory agency requirements.

Hydrologic Updates

Dam engineering is continuously evolving based on improved understanding, additional data, and lessons learned. This is particularly true when considering hydrology and development of the IDF.

Larger and more refined precipitation data sets combined with increased understanding, have prompted numerous hydrologic updates to be undertaken, both domestically and internationally. These updates can both increase and decrease precipitation depths and runoff potential as compared to those used during previous designs and evaluations.

In cases where precipitation depths increase, a dam with sufficient capacity to safely discharge the previously developed IDF may no longer have sufficient capacity to safely discharge the updated IDF and would not comply with regulatory requirements.

For scenarios in which precipitation depths decrease, existing outflow capacity is likely to be sufficient and potentially in excess of what is required from a dam safety perspective. On this basis, there could be opportunities to safely store additional water in selected existing facilities with only modest structural improvements. There are of course caveats about water rights, property rights, etc., but it can be argued that in general, the environmental permitting for an incremental increase in storage at an existing facility would require less effort than developing a new dam and reservoir from the ground up.

Regulatory Agency Updates

As industry understanding of the physical processes of precipitation and the engineering processes of runoff calculation evolve, regulatory agencies are tasked with periodically updating their rules and regulations to keep pace. Although dam owners would prefer to remain exempt from regulatory changes (i.e., "grandfathered"), regulatory agencies must maintain a common level of safety. Therefore, in the interest of public safety, grandfathering of older dams cannot be justified.

Regulatory updates pertaining to hydrologic adequacy typically impact evaluations of existing facilities with static downstream consequences and facilities where the downstream consequences have increased and their hazard classification must be changed due to the condition known as 'hazard creep.'

Hazard Classification Updates

Hazard classification updates can be initiated based on hydrologic and regulatory agency updates as well as the hazard creep resulting from development downstream of dams. Although most local zoning laws prevent downstream development from occurring within Federal Emergency Management Agency (FEMA) flood delineations, no such zoning restrictions are in place for dam failure inundation delineations. Dam failure inundation delineations are typically much more extensive than those estimated and delineated by FEMA.

This, in combination with the downstream flood protection benefits that dams often provide, can result in downstream areas becoming more desirable for development than they would be without the presence of the dam.

Figure 1. Downstream Development near the Dam Toe—a Hazard Creep Scenario [1]

A dam's hazard classification is generally based on the potential downstream consequences of a dam breach in terms of life loss as well as infrastructure and environmental damages [2], [3]; therefore, downstream development can significantly impact a dam's hazard classification and associated IDF.

Dam Owner Impacts from IDF Changes

To this point, the emphasis has been on potential changes to the IDF, but why are these potential changes so critical for a dam owner?

The hazard categories and associated IDFs required by regulatory agencies vary, however, as an example let's assume that a particular regulatory agency requires the following IDF events for each hazard classification (these requirements are typical for western states):

- Low hazard –A 1 in 100 annual exceedance probability (AEP) event (a.k.a, the 1 in 100-year event)
- Significant hazard – The 50 percent probable maximum flood event (PMF)
- High hazard – The 100 percent PMF event

Let's consider a scenario in which a small dam was originally constructed in a relatively rural area for the purpose of irrigation water supply by a local consortium of farmers. The rural area had little to no downstream development, therefore, the downstream consequences from a potential dam failure were low and the dam was classified as a low hazard structure. Over time, the downstream floodplain was gradually developed and the potential downstream consequences are now severe. As a result, the dam is reclassified as a high hazard structure—a hazard creep scenario.

Assuming the regulatory agency requirements did not change since construction, the hazard creep directly resulted in a change to the required IDF from a 1 in 100 AEP event to the 100 percent PMF event. To put this IDF change into perspective, let's further assume the required spillway discharge is 1,000 ft^3/sec for a 1 in 100 AEP event and 10,000 ft^3/sec for the PMF event.

By comparing the spillway crest length required for each of these discharges, we can illustrate the requirements associated with increasing the spillway capacity to comply with the revised IDF. Assuming a spillway discharge coefficient of 3.0 and spillway head of 5 feet, the spillway crest length required to discharge 1,000 ft^3/sec is about 30 feet. This crest length increases to nearly 300 feet to discharge 10,000 ft^3/sec —a significant increase, particularly for what was once considered a small, low hazard structure.

This type of scenario would likely be cost prohibitive to a dam owner and could lead to storage restrictions or even complete breach and abandonment of the dam. Though, prior to undertaking any major dam modifications, detailed engineering studies would need to be conducted to optimize potential modifications or potentially justify no action. These and other opportunities to address inadequacies are discussed in the following section.

Addressing Inadequacies

As previously discussed, an IDF change can be prompted due to several different factors. Upon understanding the justification for an IDF change, dam owners commonly engage in engineering studies to proactively attempt to reduce or eliminate IDF changes, particularly those driven by hazard classification changes.

Proactive Management of Hazard Creep

A dam owner has little control over development downstream of their dam, but has potentially great financial liability. By actively participating in zoning and developmental planning and discussions, a dam owner can attempt to mitigate the impacts of downstream development on a dam's hazard classification and associated IDF requirement.

State dam safety regulators are often willing to participate in community discussions regarding planning and zoning downstream of a dam. They are able to explain to local community officials the dam modifications that would be necessary to adequately protect the incoming population associated with downstream development. Many state dam safety regulators possess data to help explain the costs associated with this hazard creep. In Colorado and elsewhere, engineers must submit cost estimates as part of the design review process for all new dams and for modifications and repairs to existing dams. As such, the relative costs associated with required modifications for spillways that are the direct result of hazard creep can be estimated and used for future reference.

An additional proactive approach could include discussions and negotiations for some or all of a dam owner's costs (to address dam inadequacies relative to downstream development) to be included as part of developer costs such that the dam owner is not saddled with those expenses.

Engineering Studies

The purpose of undertaking engineering studies is to:

1) **Justify a reduced IDF, regardless of the hazard classification, based on an incremental damage assessment (IDA) –** Recognizing that consequences (i.e., life loss, damages, etc.) will be present within the downstream floodplain during extreme flood events, regardless of the performance of the dam, the basic premise of an IDA is to compare downstream consequences resulting from the IDF event with and without a dam failure. If the incremental consequences between the two scenarios are insignificant, the impact from a dam failure is considered to be negligible and a reduced IDF is justified. Lower percentages of the initial IDF event (which is usually the PMF for high hazard dams) are then evaluated until unacceptable incremental consequences are present. The IDF is then selected based on the percentage of the initial IDF at which unacceptable incremental consequences result. It should be noted that an IDA may not be appropriate or beneficial for all dam sites [2], [3].
2) **Justify reductions in probable maximum precipitation (PMP) depths and the associated IDF through site-specific PMP evaluations –** The PMP is theoretically the most severe precipitation event possible and is often assumed to result in the PMF event. The PMPs for various locations across the United States were estimated during the 1960s, 1970s and 1980s within a series of hydrometeorological reports [4] by the National Oceanic and Atmospheric Administration (NOAA). These studies were performed for large scale regions based on the data and understanding available at the time of each study. Using modern techniques and updated data sets, site-specific PMP studies have been used to justify reductions in design PMP depths of up to about 40 percent. As a result of these reductions in maximum precipitation estimates, the IDF can be reduced. It should be noted that site-specific PMP studies may not always result in a reduced IDF. Although rare, revised PMP depths have increased in some locations as a result of site-specific studies.
3) **Develop dam modification alternatives to safely discharge the IDF event –** If engineering studies to justify a reduced IDF are not appropriate or effective, dam modification alternative evaluations are required. The development of modification alternatives include numerous considerations and are discussed in the following section.

Dam Modification Alternatives

Dam modification alternatives developed to safely accommodate an increased IDF could include one or more of the following:

- Existing spillway modifications
- New spillway construction
- Dam crest modifications

Existing Spillway Modifications

Increasing the capacity of an existing spillway is one method that can be used to accommodate an increased IDF. Modifications to increase existing spillway capacity could include:

- More efficient approach conditions
    - Sloped approach to weir crest
    - Rounded or curved abutments to reduce flow separation and loss of effective spillway crest length
- A more efficient spillway crest
    - Sharp crest weir
    - Ogee crest weir
    - Rounded or curved crest shape
- A longer spillway crest
    - Linear weir
    - Labyrinth weir
    - Curved or arced weir
- Lowering the spillway crest elevation to increase available spillway head
    - Loss of normal storage capacity would occur, but could be offset by use of fusing elements like fusegates or fuseplugs

Combinations of these potential modification alternatives should also be considered when optimizing a balance between project objectives and construction cost.

Figure 2. Arced Weir Spillway [5]

Figure 3. Labyrinth Weir Fusegate Spillway [6]

Regardless of the adopted modification arrangement, it is critical to evaluate the performance of existing structures and features relative to the increased outflows. These features and evaluations could include:

- Chute erosion potential, particularly for chutes without concrete lining
- Chute slab uplift potential
- Chute wall overtopping potential
- Cavitation potential
- Adequacy of energy dissipation

Additionally, increasing spillway capacity to accommodate the IDF can increase spillway outflows associated with more frequent events, which can have unacceptable downstream consequences. This potential condition should be evaluated and considered as part of modification designs to ensure that potential incremental downstream consequences are minimized.

Furthermore, the design of spillway modifications should include detailed evaluations of foundation conditions and structural stability, including earthquake load conditions.

New Spillway Construction

Where existing spillway modifications alone are insufficient or impractical, increasing the overall outflow capacity can be accomplished by adding an additional spillway. The placement of an additional spillway is often constrained by site-specific conditions; however, it is common to site new spillways within one of the dam abutments or somewhere along the reservoir rim.

These types of spillways are typically earth or rock cuts and can be lined or unlined depending on hydraulic conditions, erosive potential, and risk tolerance. Careful consideration of the impacts both proximate to the dam and new spillway as well as downstream is required to avoid creating unnecessary adverse consequences.

It is generally discouraged to site a spillway of any kind (i.e., principal, emergency, etc.) over a dam embankment due to increased dam failure potential resulting from increased embankment seepage and hydraulic structure failure potential. If site conditions constrain selection of a new spillway to over the dam, overtopping protection could be a more desirable alternative than a structural spillway.

Overtopping protection of embankment dams can be used to increase the overall outflow capacity in lieu of constructing a new spillway over the dam, abutments or reservoir rim. Overtopping protection can be constructed using a variety of materials, the most common being roller compacted concrete (RCC), conventional concrete, articulated concrete blocks (ACB) and soil cement. Regardless of the overtopping protection material, operation of an overtopping spillway should be limited to infrequent and extreme events to reduce the risk of potential dam failure [7].

Figure 4. RCC Overtopping Protection Installation

Figure 5. ACB Overtopping Protection

Overtopping of concrete dams can be acceptable on a more frequent basis if structural evaluations confirm dam stability and adequate downstream energy dissipation is provided or erosion resistant material is present.

The design of new spillways should include detailed evaluations of:

- Foundation conditions
- Spillway crest types and shapes
- Energy dissipation structures
- Structural stability, including earthquake load conditions
- Potential incremental downstream consequences for more frequent events.

Dam Crest Modifications

In lieu of constructing modifications to increase overall outflow capacity directly, dam crest modifications are another alternative used to provide capacity to safely discharge an increased IDF. By raising the dam crest elevation, the benefits to outflow capacity are twofold:

- Additional flood storage surcharge volume is provided, which can be particularly effective in attenuating flood inflows and reducing the spillway capacity requirements associated with the short duration, high intensity storm events commonly observed across the western states.
- Raising the dam increases the spillway head, resulting in increased spillway capacity. Spillway capacity is a function of spillway head (H), a crest efficiency coefficient (C), and crest length (L) [8]. The spillway head is raised to the three halves power, whereas, the spillway crest coefficient and length are raised to the power of unity ($Q=CLH^{3/2}$), making the dam raise exponentially effective.

A dam crest raise can be a very efficient, simple, and economical solution to providing additional outflow capacity. Dam crest raise alternatives commonly include:

- Conventional upstream, downstream, or centerline embankment raises
- Parapet or other conventional concrete walls
- A variety of reinforced/retaining earth walls

Figure 6. Dam Crest Raise with a Concrete Parapet Wall [9]

Although the normal reservoir water surface elevation will not change by raising the dam crest elevation, the flood pool will change, particularly for infrequent food events. The potential impacts of these flood pool increases should be evaluated to confirm that they do not pose unacceptable consequences. Furthermore, the impact of increased spillway outflows on existing features should also be evaluated to confirm satisfactory performance.

Consideration should also be given to specific site conditions including, but not limited to:

- Practical dam raise heights due to topographic limits
- Abutment tie-in locations and the associated dam crest length
- The potential need for saddle dams
- Foundation conditions
- Compliance with local water laws regarding the maximum detention time of flood storage

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Internal Erosion: Issues Just Below the Surface

Introduction

Internal erosion is one of the leading causes of embankment dam failures, second only to overtopping failures. Internal erosion occurs when embankment or foundation soil particles are transported downstream by seepage flow. The erosion begins when the seepage force exceeds the erosion resistance of the materials. Erosion resistance is a function of several soil properties as described later in this article. Modern earthfill dam design usually incorporates embankment zoning that includes a low permeability core as the seepage barrier, upstream and downstream shells for structural support, and an internal filter and drainage system to intercept seepage and reduce the probability of material transport. The use of filters in modern dams has been proven an effective and reliable method to protect against internal erosion. That is, when the filter system is designed and constructed properly. However, many older and smaller dams are not adequately zoned to provide the preferred level of protection against internal erosion.

Internal erosion issues can become apparent on first filling or after many years of operation. During first filling, the materials are subjected to new seepage flow and gradients that had previously not been experienced. Aging dams may experience changes in forces due to continued settlement from reservoir drawdown cycles, deterioration of pipes and structures, or exposure to an extreme flood or seismic event. In some cases, internal erosion is such a slow-moving failure mode that signs of it occurring take years or decades to first appear.

Internal erosion has been a topic of much interest, research, and publication over the past 30 years, and continues today. This is a potential failure mode that cannot be completely analyzed using numerical formulae or models. As our understanding of internal erosion mechanisms evolves, valuable information on dam and soil behavior is becoming available to help in assessing internal erosion risks. This article summarizes key information needed to gain a fundamental understanding of internal erosion mechanisms and presents a high level summary of some key parameters that influence the likelihood of internal erosion occurring and progressing. Two recent publications are excellent references for more comprehensive details on the topic: see references [1] and [2] at the end of this article. Look for future articles in Technical Note that will discuss methods of seepage remediation, mitigation, and emergency preparedness.

Internal Erosion Process

Internal erosion occurs when seepage through voids within a soil or rock mass exert hydraulic forces sufficient to detach and transport particles. The loss of material from within an embankment or foundation can lead to significant deformation and eventually breach of the dam. The process is often localized along a crack, defect, or high seepage velocity zone that expands as erosion progresses. There are four general seepage paths by which internal erosion can occur:

1. Through the embankment
2. Internal erosion of the embankment into or along the foundation or abutments
3. Through the foundation
4. Along or through penetrating structures (conduits or structural walls)

For all failure paths, the typical series of events to describe the mode of failure from initiation to complete breach, known as an event tree, has been developed and is generally described as follows [1]:

1. Reservoir is at or above threshold level.
2. Initiation of erosion – a defect exists that allows soil particles to be transported out of the embankment or foundation by seepage flow.
3. Continuation – particle transport is not hindered by a downstream filter.
4. Progression – eroding material leads to sloughing of slope or the formation of a pipe through a continuous stable roof and/or sidewalls.
5. Progression – Constriction (i.e., cutoff wall or rock joint) or upstream zone fails to limit flows.
6. Progression – No self-healing by upstream zone (e.g. crack stopper or upstream shell fails to clog developing void.
7. Detection and intervention are unsuccessful.

8. Breach – deformation from loss of material becomes large enough to result in embankment collapse and potential overtopping.

For internal erosion to lead to failure, conditions must exist for the full sequence of events to occur. However, significant damage to the dam can still take place as the failure mode progresses through each step of the event tree, even if human intervention or natural events prevent failure from occurring.

Mechanisms of Internal Erosion Initiation

The term “internal erosion” is the industry’s generic term to describe erosion of soil particles by water passing through a body of soil. “Piping” is often used generically in literature, but actually refers to a specific internal erosion mechanism. There are four mechanisms by which internal erosion can initiate:

1. Backward erosion piping (BEP)
2. Concentrated leak erosion
3. Contact erosion
4. Suffusion/suffosion

The conditions of each mechanism vary but all can result in sufficient migration of material from within the dam’s footprint leading to significant dam deformation or breach.

Backward Erosion Piping (BEP)

BEP is characterized by the detachment or erosion of particles at the exit of a seepage path and the propagation of that path upstream towards the reservoir. Movement occurs because of high gradients at the exit location, usually a free surface on the downstream slope or toe. The erosion is sustained because of a “roof” formation that maintains a small “pipe” that works backward from downstream toward the reservoir. BEP generally occurs in erodible non-plastic soils that are overlain by more cohesive materials or conditions that promote arching to sustain a “roof.” Sand boils at the downstream toe are the most common sign that BEP could be occurring.

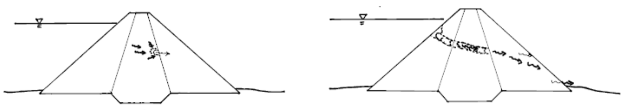

Figure 1. Backward Erosion Piping Through the Embankment [2]

Figure 2. Sand Boil at Downstream Toe of Earth Dam

Global backward erosion is the name given to the type of backward erosion in which the soil above or around a backward erosion pipe is unable to ‘hold a roof.’ This is also referred to by Reclamation as “Internal Migration.” Incipient backward erosion pipes form but soon collapse resulting in general movement of the soil from above. There are two subset mechanisms within “Global BEP,” depending on how the collapse of the pipe or void occurs: sloughing and stoping.

Sloughing

When BEP occurs at the downstream slope due to seepage breakout at the face, it can develop in the form of progressive sloughing of soil. Seepage exiting the free downstream face may be sufficient to begin removing and washing away particles at the face. The process works by gravity and the failure mode becomes one of unraveling of the downstream slope. The process may continue in a step-wise fashion toward the reservoir until a breach is formed through the dam as shown in Figure 3.

CAUTION

Digging at the downstream toe of an embankment dam for investigation or remediation can initiate an unfiltered seepage exit. Particularly if the pool is, or was recently full. This can quickly trigger internal erosion failure modes and require quick response. Uncontrolled seepage can be triggered by simply removing the vegetation layer which can serve as a cap on pervious soils. Know where the water table is before you dig and have a pre-planned emergency response action ready to implement.

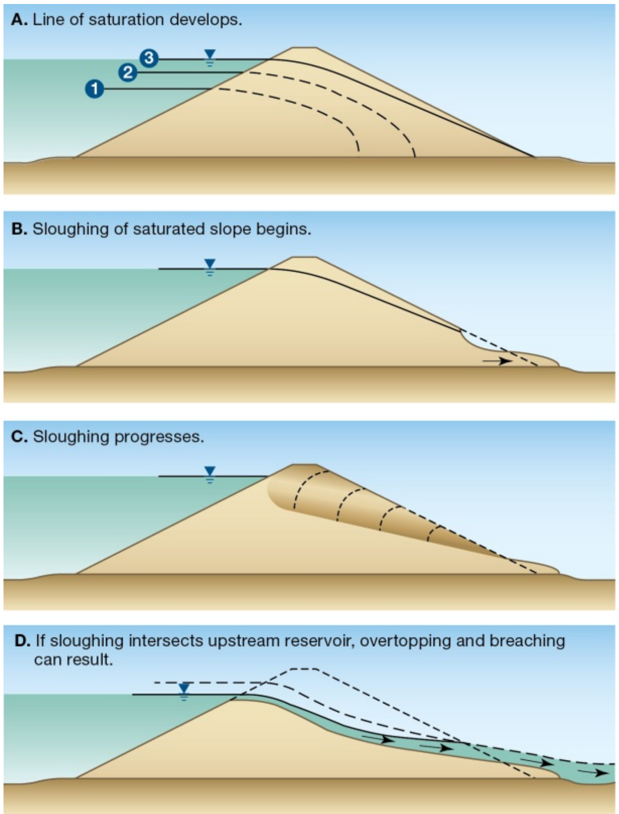

Figure 3. Illustration of how downstream progressive sloughing due to saturation could lead to dam failure [Adapted from [5]]

Stoping

If the collapse is in the upward direction, it can lead to a near vertical cavity in the embankment. Particle movement is driven by gravity and the stoping process progresses in a more vertical/upward direction (rather than horizontal/upstream) and may eventually express itself as a sinkhole near the dam crest.

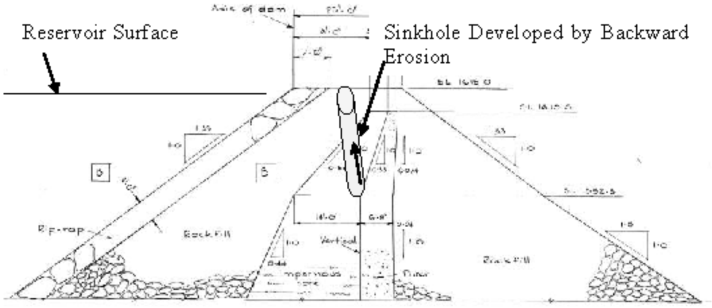

Figure 4. Stoping Leading to Formation of a Sinkhole in a Narrow Sloping Core [2]

Concentrated Leak Erosion

Erosion of material along the sides of an opening or crack is considered concentrated leak erosion. This can also be known as a scour mechanism, as the material is scoured from the sides of the void by the force of moving water. Plastic soils and some unsaturated silts and sands can hold an opening or crack that would be susceptible to concentrated leak erosion. Causes of cracks or openings include differential settlement, hydraulic fracture along a low stress zone (at conduits and low compaction zones), desiccation, collapse settlement around poorly compacted material (at conduits and vertical walls), collapse of foundations soils and animal burrows or rotting tree roots causing voids. Ponding and seepage with particle transport on the downstream face, around conduits or at the downstream toe, are all signs that concentrated leak erosion could be occurring.

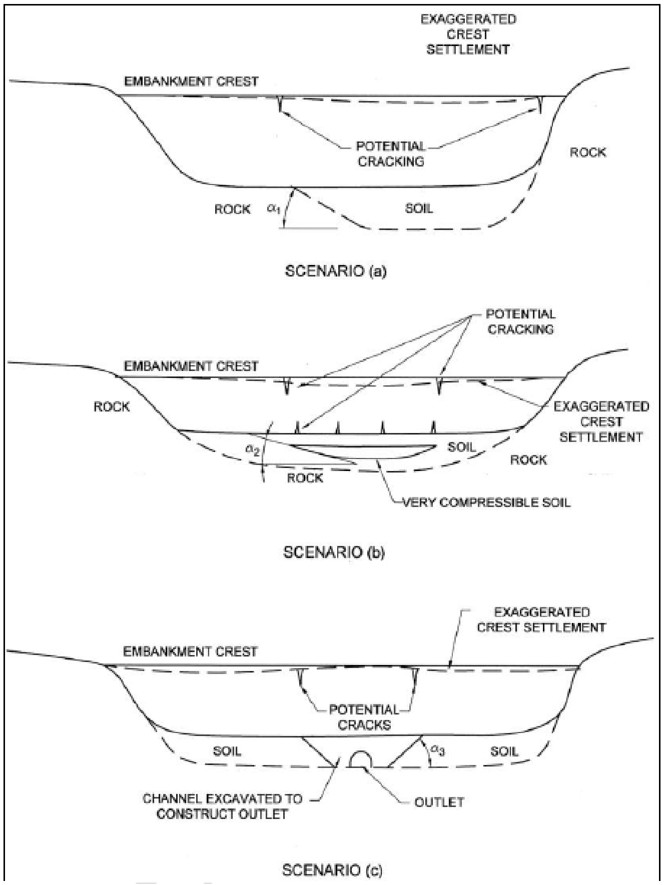

Figure 5. Common Crack Locations for Concentrated Leak Erosion, [3], [4]

Figure 6. The Result of Concentrated Leak Erosion along a Conduit at a Dam in Montana

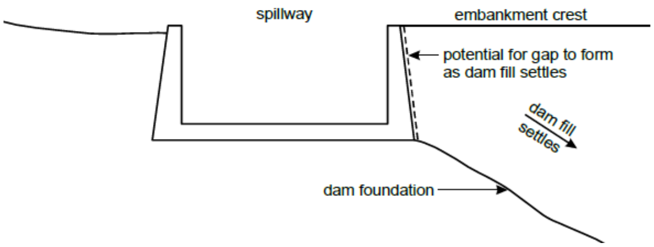

Figure 7. Common Crack Locations for Concentrated Leak Erosion along Abutting Structures [2]

Contact Erosion

Contact erosion is often confused with concentrated leak erosion; both are scour type mechanisms in which seepage scours the material from a surface. In concentrated leak erosion, the seepage occurs through cracks, low stress zones, or voids; in contact erosion, the seepage occurs through a pervious, coarse stratum that is in contact with an erodible layer. Contact erosion occurs when coarse material is in contact with finer material and the flow path is parallel or along the interface of the materials. The larger flow through the more pervious coarse material scours or erodes the adjacent finer material, transporting it through the void space of the coarser materials.

This failure mode is most common at the interface between the embankment and foundation, where gravity assists in moving the finer materials down and into the coarser foundation. It can also occur within the foundation between geologic layers or between embankment layers that occurred due to segregation during construction. Contact erosion does not refer to preferential seepage along contacts with structures such as concrete sections, retaining walls, or rock abutments (see Concentrated Leak Erosion). Sand boils at the downstream toe, particles in downstream channels and irregular settlement of the crest are the most common signs that contact erosion could be occurring.

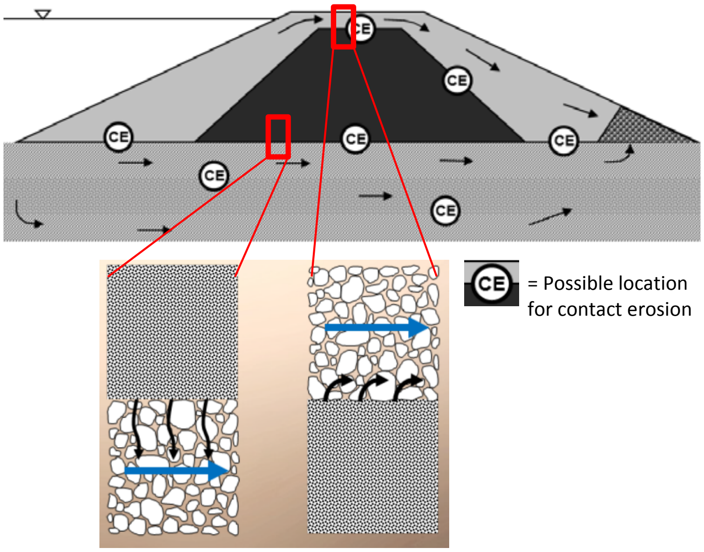

Figure 8. Contact Erosion Process (adapted from [1] [2])

Suffusion/Suffosion

In materials that are widely graded or gap graded, fine particles can erode from within the matrix of the coarse particles when subjected to seepage flows. The materials are considered internally unstable and it can lead to an increase in permeability, greater seepage velocities and potentially higher hydraulic gradients, all resulting in an accelerating rate of suffusion. When the coarse particles are densely packed and in point-to-point contact with each other, the transport of fines out of the matrix results in little to no volume change. This is referred to “suffusion” and is depicted on Figure 9 (a). Particles in downstream channels or low points, leakage on the downstream slope, and irregular settlement of the crest are the most common signs that suffusion could be occurring.

When the coarse particles are more loosely packed, the transport of fines out of the matrix results in a reduction in total volume, and the process is referred to as “suffosion.” Suffosion can lead to settlement or instability and eventual collapse or significant deformation of the embankment.

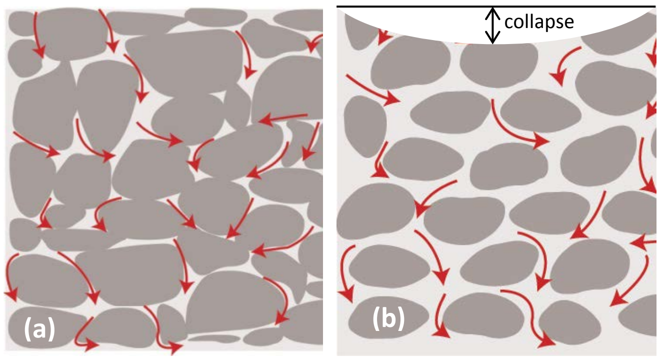

Figure 9. (a) Suffusion and (b) Suffosion Processes

Internal Erosion Potential Failure Modes

The potential internal erosion failure mode by which a dam may fail depends on the mechanism that occurs and its location. Table 1 summarizes the mechanisms that are often applicable to specific potential failure modes. The table highlights the most common mechanism(s) for each failure mode.

Table 1 - Internal Erosion Mechanisms by Failure Mode

Failure Mode Pathways Internal Erosion Mechanisms	Through Embankment	Through Foundation	Into Foundation or Abutment	Along/Into Conduit
BEP	X	**X**	X	X
Concentrated Leak	**X**	X	**X**	**X**
Contact	X	**X**		
Suffusion/Suffosion	X	X		

Bolded Xs represent the most common mechanism(s) for each failure mode.

All four mechanisms can occur within internal erosion through the embankment and internal erosion through the foundation. For internal erosion of the embankment into the foundation or abutment, BEP and concentrated leak erosion can occur. For internal erosion along/into conduits or pipes, concentrated leak erosion is often the primary mechanism unless the material along the conduit is low-plasticity or otherwise erodible for the full pathway.

Internal Erosion through Embankment

When BEP leads to internal erosion through the embankment, it generally exits near the downstream toe of the embankment where, the phreatic line is close to the ground surface and exit gradients are highest. Signs that BEP may be occurring within the embankment include localized deformation, collapse, and sedimentation on the slope or toe.

Concentrated leak erosion through a crack in the embankment can occur due to differential settlement from unfavorable geometry, hydraulic fracturing, desiccation cracking, earthquake induced cracking, low stress or compaction zones, arching at concrete penetrations or abutment walls, construction defects or voids from roots or animal burrows. Signs of concentrated leak erosion through the embankment include sediment deposition on the downstream slope or toe, enlargement or multiplication of surface cracks, and downstream slope bulging.

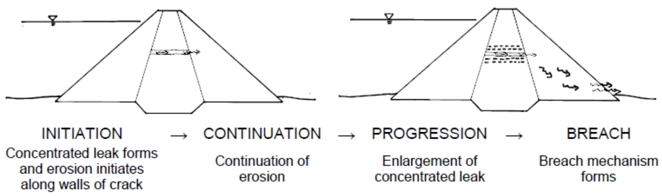

Figure 10. Internal Erosion through the Embankment by Concentrated Leak Erosion [2]

Figure 11. Seepage through the Embankment at Blackmon Dam in Tasmania

Contact erosion can occur due to seepage through a pervious zone above a core that does not extend to the surface. Suffusion and suffosion can occur if embankment materials are poorly or gap-graded. Cloudy seepage out of the embankment or the deposition of fine material at the toe can indicate suffusion or suffosion is occurring. Larger than normal settlement or deformation can be a sign of suffosion.

Internal Erosion through Foundation

BEP through the foundation is initiated at an unfiltered exit downstream of the embankment toe. The exit can exhibit heave or uplift/blowout as well as sand boils. The foundation material must be erodible for BEP to occur, but the cohesion necessary to form a pipe could come from an overlying confining layer, producing a failure path along the interface. Concentrated leak erosion can occur due to arching through a crack in the foundation created by differential settlement or collapse, and arching across formations or irregularities in the foundation.

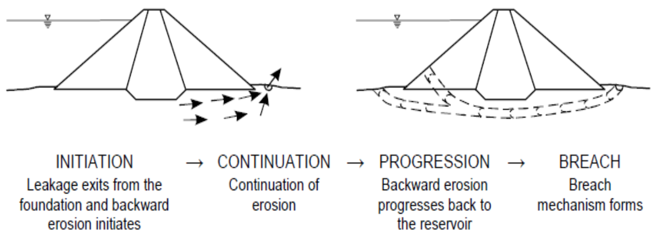

Figure 12. Internal Erosion through the Foundation by BEP [2]

Figure 13. Seepage through Foundation Exiting at Downstream Toe of Earthen Dam

Contact erosion can occur through the foundation when a pervious foundation layer underlies a fines layer (e.g., the overlying embankment or a fine-grained foundation layer) allowing for water flow in the permeable layer to transport the fines of the adjacent fine layer.

Suffusion or suffosion can occur in the foundation if there are poorly or gap-graded layers allowing for the fine material to move through and out of the coarser material matrix. Sediment deposition in downstream ditches or channels can be an indication of concentrated leak erosion, contact erosion or suffusion/suffosion. Larger than normal settlement or deformation can be a sign of suffosion. See our previous article for more information on mechanisms for internal erosion through the foundation: "IS YOUR EMBANKMENT DAM UNDER PRESSURE - UNDERSEEPAGE IMPACTS".

Internal Erosion of Embankment into Foundation or Abutment

BEP, contact erosion, and concentrated leak erosion can initiate at the interface between the embankment and foundation (including the abutment) by transporting embankment material into a void, joint, or other opening in the foundation. BEP can occur when gradients at the interface are large enough to transport embankment material into a permeable foundation or abutment and the embankment material is cohesive enough to hold a roof. Concentrated leak erosion can occur when a defect in the foundation or abutment (e.g., a fracture) concentrates seepage, and embankment material is scoured by the flow. Contact erosion occurs when the permeability and porosity of the foundation or abutment is significantly higher than adjacent embankment material, resulting in greater flow velocity through the foundation or abutment. The difference in flow velocity at the interface of the materials allows for embankment material to be transported into the foundation or abutment. Sinkholes or depressions in the embankment and sediment deposition downstream in channels or ditches are signs that any of the three internal erosion mechanisms may be occurring through the embankment and into the foundation or abutment.

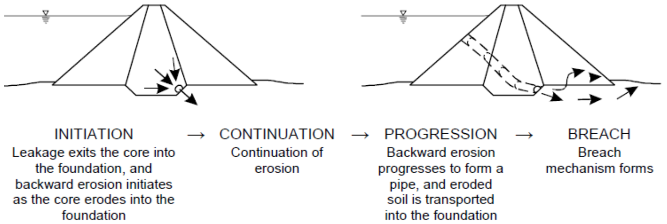

Figure 14. Internal Erosion of the Embankment into the Foundation by BEP [2]

Figure 15. Partial Failure of Fontenelle Dam Due to Internal Erosion into Untreated Fractures in the Foundation [5]

Internal Erosion along/Out of/into Conduits or Drains

Concentrated leak erosion can occur along conduits due to cracks or low stress zones around conduits from poor compaction during construction or differential settlement. BEP may be the initiating mechanism when the material along the full pipe length comprises low-plasticity erodible material. The seepage flow can be from reservoir head or from a hole in a conduit that is flowing under pressure. The material usually exits downstream around the daylight of the conduit. If a crack or hole occurs in a conduit not flowing under pressure, concentrated leak erosion can cause material to be transported into the conduit. Sediment in the conduit discharge or clogging of the conduit can be a sign of concentrated leak erosion into the conduit. Sinkholes and depressions on the embankment surface can also be signs that erosion is occurring along or into the conduit below.

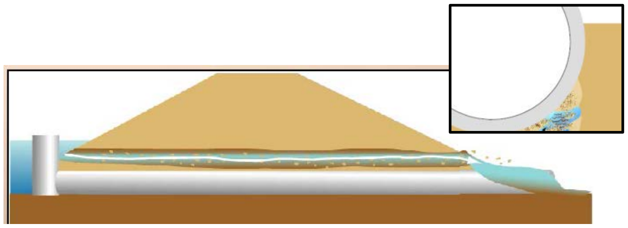

Figure 16. Internal Erosion along a Conduit [1]

Figure 17. Internal Erosion along Conduits is a Common Failure Mode for Dams prior to the Use of Filter Diaphragms [1]

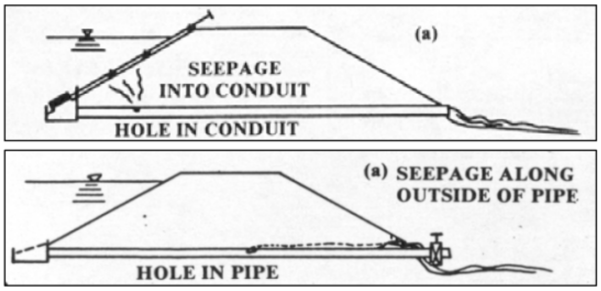

Figure 18. Internal Erosion into and out of a Conduit [1]

Figure 19. Sinkhole in crest of a dam in Montana that manifested after several years of undetected internal erosion into a damaged conduit [6]

Conditions for Initiation of Internal Erosion

For internal erosion to initiate, certain conditions need to exist within the dam. The material properties, hydraulic load, and critical stress conditions all play a part in the initiation, continuation, and progressions. Figure 20 below summarizes how different factors contribute to conditions for internal erosion to occur.

Material Properties

The erodibility of a soil is the major factor in the probability of internal erosion occurring and is a function of material properties including particle size, plasticity and gradation. Cohesionless materials (low plasticity) such as sands and silts are more likely to erode than those with cohesion (such as clays) as the particles have fewer internal forces keeping the particles together.

Fine-grained sand and silt particles are more likely to erode than larger, coarse particles (as in coarser sands and gravels, cobbles, and boulders) because it takes more energy (seepage velocity) to move larger, heavier particles. The gradation distribution of a material is also important as a well-graded material may provide its own filtering in that the larger materials provide the weight needed to counteract movement, while the smaller materials fill voids and reduce permeability and therefore, seepage velocity. More uniformly graded soils are therefore more susceptible to erosion than well-graded soils.

Broadly-graded soil (soils with a wide range of particle sizes; e.g. ranging from cobble to silt sizes) can be susceptible to internal instability (suffusion or suffosion). This is particularly true when the gradation distribution lacks certain particle sizes, known as gap-graded soils. In these soils, the coarser fraction of the soil is too large to filter the finer fraction.

Table 2. Internal Erosion Potential of Soils (Adapted from [4])

Greatest Piping Resistance Category (1)	1. Plastic clay (PI>15), Well compacted
	2. Plastic clay (PI>15), Poorly compacted
Intermediate Piping Resistance Category (2)	3. Well-graded material with clay binder (6<PI<15), Well compacted
	4. Well-graded material with clay binder (6<PI<15), Poorly compacted
	5. Well-graded cohesionless material (PI<6), Well compacted
Least Piping Resistance Category (3)	6. Well-graded cohesionless material (PI <6), Poorly compacted
	7. Very uniform, fine cohesionless sand (PI<6), Well compacted
	8. Very uniform fine cohesionless sand (PI<6), Poorly compacted

Note: Dispersive soils may be less resistant than Category 3.

Hydraulic Load

Hydraulic gradients and seepage velocities are also key factors in determining the potential of internal erosion. For simplicity, average (horizontal) gradients along the entire suspected internal erosion pathway are usually estimated to evaluate the potential for internal erosion to occur, as it is difficult to measure in the field. Several researchers have measured erosion potential in the past and determined gradients at which certain soils may erode. However, conditions in the field contain many more uncertainties than laboratory environments used for testing, and BEP has been estimated to occur with gradients less than 0.05. Based on laboratory testing, the initiating gradient to erode sands is a function of the gradation, with poorly (more uniformly) graded sands being more susceptible to erosion at lower gradients than well graded soils. Upward, or vertical, gradients can be estimated in cases where a confining layer exists at the downstream exit point. The vertical gradients relate to the potential for heave or uplift to initiate erosion at the exit point and are impacted by the properties and thickness of the confining layer. (See the previous Tech Note article "IS YOUR EMBANKMENT DAM UNDER PRESSURE - UNDERSEEPAGE IMPACTS")

Stress Conditions

The stress conditions that most influence the potential for internal erosion are those that create defects or occur at naturally occurring defects. Cracking from differential settlement can occur when there are irregularities in foundation geometry, large differences in embankment height, rigid elements within the embankment (conduits), or differences in compressibility of foundation or embankment material. Foundation defects can include bedrock joints, fractures, bedding planes, folation, shears, and faults. The size and continuity of the foundation defects, as well as the effectiveness of any foundation treatment, are factors in the potential for internal erosion to occur. Foundations with karstic or solutioning properties show a history of sinkholes and caves and can be a major concern for internal erosion of the embankment into the foundation.

Hydraulic fractures can form when hydraulic pressures exceed minor principal stresses between material particles. This can be due to areas of low stress causing arching, improper drilling methods being used in the core of a dam, or when a slurry trench cutoff is installed as a seepage barrier. However, hydraulic fractures can sometime close as stresses redistribute or materials saturate and expand.

High permeability or low stress zones can be caused by a wide range of construction related issues. Low stress zones around conduits and structure walls can occur due to difficult or inadequate compaction especially under a conduit, around cutoff collars, or next to a steep or vertical wall. High permeability zones within an embankment can occur due to poor compaction from low density material, thick lifts, and too much or too little water content. Poor quality control of material can lead to segregation and layers or pockets of coarse material. Poor treatment of foundation bedrock prior to placement of the embankment can create high permeability seams at the contact. Layers exposed to freezing or significant precipitation can experience a decrease in density, and desiccation cracking can occur in those exposed to high heat. Rodent burrows or root systems from vegetation can also create defects in the embankment that can lead to propagation of cracks or piping.

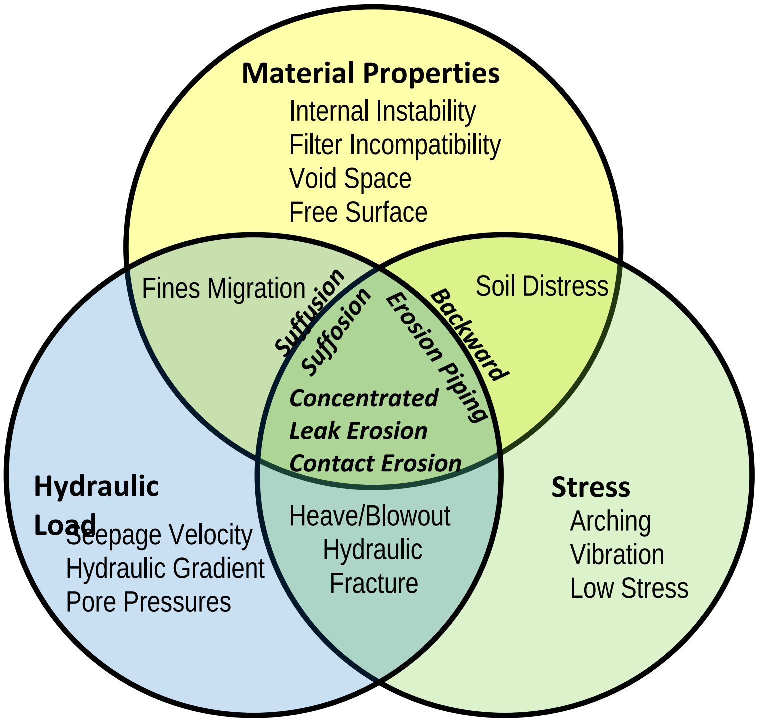

Figure 20. Factors Affecting the Initiation of Internal Erosion (Adapted from [2], [5])

Filters!

There have been no documented case histories of a dam failing through internal erosion when the use of an engineered filter has been incorporated in the design. Filters located downstream of an erodible material are effective at arresting all internal erosion mechanisms. Filters and transition zones of coarse particle size can be effective in controlling erosion even when not designed as an engineered filter. See our previous article on "Filter Design and Construction."

Conclusion

Internal erosion remains one of the main causes of failures and accidents at embankment dams worldwide and warrants a heightened understanding. Therefore, it is important that the mechanisms and conditions by which internal erosion can occur, and the related warning signs should govern surveillance and monitoring for embankment dams. Visual inspection, measuring seepage, and monitoring pore pressures are essential tools in identifying signs of internal erosion Look for future articles that will cover monitoring and remediation of seepage failure modes, but in the meantime a recent document by the Federal Emergency Management Agency (FEMA) on monitoring for seepage is an excellent reference on the topic (See reference [6]).

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