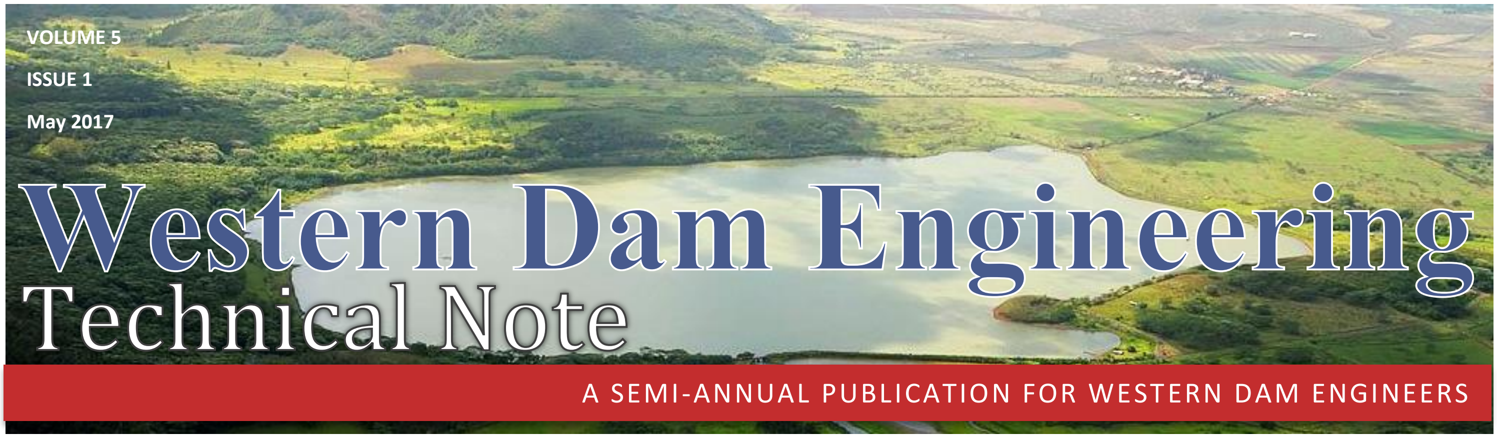

VOLUME 5

ISSUE 1

May 2017

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 **emergency response to seepage and internal erosion**, **certainty and uncertainty of hydrologic modeling results**, and **inspections of corrugated metal pipes**. 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.

The Western Dam Engineering Technical Note is sponsored by the following agencies:

- Colorado Division of Water Resources
- Montana Department of Natural Resources
- Wyoming State Engineer's Office
- New Mexico Office of the State Engineer

This Technical Note was compiled, written, and edited by AECOM in Denver, Colorado

Funding for the Technical Note has been provided by the FEMA National Dam Safety Act Assistance to States grant program.

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In this Issue

Thinking Fast - Emergency Response to Seepage and Internal Erosion

Introduction

One of the most challenging threats to the safety of an earthen dam is concentrated, uncontrolled seepage that has initiated internal erosion. The progression of such an event may be avoided by inspection, monitoring, maintenance, and, if warranted, rehabilitation. But what if those measures have not been implemented, or in spite of them there is a failure to recognize a progressing problem, and it culminates in an emergency situation? This article focuses on answering that question.

The previous Western Dam Tech Note article titled Is Your Embankment Dam under Pressure – Underseepage Impacts describes the mechanics, monitoring, and investigation of seepage through the soil foundations of earth dams in some detail, and provides a good background to the following discussion.

Why we care about concentrated seepage

As shown in Table 1 more than half of all dam failures worldwide in the modern dam era have been due to seepage-induced piping (i.e., internal erosion). Failures and incidents continue to happen today, incurring significant consequences to the owner and the public.

From January 1, 2005 through June 2013, state dam safety programs reported 173 dam failures and 587 "incidents" - episodes that, without intervention, would likely have resulted in dam failure [1]. Examples of incidents involving concentrated seepage that could have led to dam failure without timely, aggressive, and ultimately successful intervention include:

- AV Watkins Dam, UT [2,3,4,5]
- Lake Needwood Dam, MD [4,6,7]
- Washakie Dam, WY [4,8,9]
- Powell Dam, MT [4] – see inset this page
- Salt Fork Dam, OH [4] – see inset next page

Brief case histories of concentrated seepage events at AV Watkins, Lake Needwood and Washakie Dams are presented at the end of this article.

Table 1. Seepage-Induced Internal Erosion Dam Failures Worldwide [2].

Mode of Failure	% Total Failures (where mode of failure was known)	% Failures pre 1950	% Failures post 1950
Overtopping	34.2%	36.2%	32.2%
Spillway/gate (appurtenant works)	12.8%	17.2%	8.5%
Piping through embankment	32.5%	29.3%	35.5%
Piping from embankment into foundation	1.7%	0.0%	3.4%
Piping through foundation	15.4%	15.5%	15.3%
Downstream slide	3.4%	6.9%	0.0%
Upstream slide	0.9%	0.0%	1.7%
Earthquake	1.7%	0.0%	3.4%
Totals (1)	102.6%	105.1%	100.0%
Total overtopping and apurtenant works	47.0%	53.4%	40.7%
Total piping	49.6%	44.8%	54.2%
Total slides	4.3%	6.9%	1.7%
Total no. embankment dam failures (exc. During construction(	124	61	63
Total embankment dam years operation (up to 1986)	300,400	71,000	229,400
Annual probability of failure	4.1×10^{-4}	8.6×10^{-4}	2.7×10^{-4}

(1) Subtotals and totals do not necessarily sum to 100% as some failures were classified as multiple modes of failure

Powell Dam Foundation Seepage Blowout

Construction of a seepage berm likely concentrated the seepage exit from a gravel layer to the edge of the berm, causing a blowout (see photo to left). Emergency response included the placement of on-hand woven-geotextile fabric covered with stockpiled drain rock (see photo below). A permanent toe drain was later constructed to intercept and drain the gravel layer believed to be the source of the high pressures.

Salt Fork Dam Boil

A 4-ft diameter boil appeared at the toe of the dam, following a record high pool. The boil was cloudy, with soil particles moving at the bottom. The boil was caused by surcharging of a clogged toe drain by flows from the right abutment. A sandbag ring was constructed around the boil and a V-notch weir installed to monitor flow (see Figure 7 for a similar installation). The amount of flow coming into the lake made it impossible to quickly lower the lake level. The use of large pumps to assist with the drawdown was not an option, due to high cost and availability. Excavating through an abutment to drain the lake was considered, but since both abutments are bedrock, this idea was abandoned. A weighted inverted filter berm over the boil consisting of pea gravel overlain by concrete sand was constructed (see Figure 3).

Recognizing the First Signs of Trouble

What should we be looking for?

Examples of conditions that should be noted for vigilant monitoring include:

- *visible seepage exits*
- *unexplained wet areas or lush vegetation*
- *unexplained increases in downstream weir or channel flows*

Examples of conditions that should immediately raise concern are:

- *whirlpools in the reservoir*
- *sinkholes anywhere on the dam, abutments, downstream toe or reservoir pool*
- *new sand boils, blowout holes, pluming, or sediment deposited at a visible seepage exit.*
- *concentrated seepage around conduits or elsewhere on the dam, at the downstream toe or in the abutments*

Dam inspections and monitoring are essential activities that can help avoid, or at least provide timely warning of, developing seepage conditions to allow for successful intervention. These topics are discussed in previous Western Dam Tech Note articles titled, "Dam Safety Inspections – A Closer Look" and "Does Your Dam Measure Up? – Developing an Effective Instrumentation Program for Small Earth Dams.

Intervention Planning

A key part of responding as effectively as possible to a serious seepage incident is preparation. One concept that is gaining attention is to develop an Emergency Intervention Plan (EIP). This can either be a stand-alone document or an appendix to the Emergency Action Plan (EAP). Guidance on developing an EIP is contained in the Dam Owner Emergency Intervention Toolbox [10]. Preparatory actions may include stockpiling of on-site materials, identifying owner's on-site equipment, and making arrangements to be able to call on outside resources (experts, labor, equipment and materials), as addressed further below.

Assess the Situation

It is critical in responding to a serious seepage incident that conditions be assessed and documented as a basis for identifying and implementing the appropriate response actions. The assessment and early stages of the response should address all of the following topics, and others that may come to mind:

- ✓ *Perform an initial assessment – quick, but thorough; look for the big items and don't get bogged down in details that can be dealt with later.*
- ✓ *Determine the "emergency level" as defined in the EAP and make appropriate notifications and contacts.*
- ✓ *Update initial assessment as often, as needed.*
- ✓ *Confirm site access – are routes outlined in the EAP open and passable? Are alternate routes needed?*
- ✓ *Note current and forecast weather conditions*
- ✓ *Observe reservoir pool level – is it or has it been dropping at a rate greater than anticipated based on existing inflows and normal outlet releases?*
- ✓ *Identify known or potential water entry areas (whirlpools, sinkholes in the reservoir pool area) and seepage exit areas (diffuse and/or concentrated seepage, sinkholes, around outlet or other conduits).*
- ✓ *Estimate or measure seepage flow.*

- ✓ *Check for entrained sand or fines.*
- ✓ *Observe and record increases or decreases in flow.*
- ✓ *Observe and record secondary effects (slumping, sliding, erosion, deposition).*
- ✓ *Check availability of off-site materials, equipment, labor, and professional resources – how much and how soon?*
- ✓ *Assign roles to available support staff: monitoring the incident area, media/public management, coordination of off-site resources, coordination of emergency response staff, etc.*
- ✓ *Begin brainstorming potential courses of action.*

Talk with the dam tender or other personnel familiar with the dam. See if they can be present as you do the assessment.

Documentation does not need to be extensive and overly detailed; get the key facts and observations. Digital photos and videos are immensely helpful. Include recognizable features in the view and record from more than one vantage point to document proper perspective. Taking notes on a set of as-built drawings is efficient and effective.

The results of the initial assessment will guide the appropriate next actions to take, as discussed in the following section. But be flexible and respond to changing conditions on the ground, including weather, availability of staff, equipment and materials, and especially the seepage behavior.

Concentrated Flows vs. Disperse Seepage

The characteristics of the exiting seepage related to the internal erosion incident will influence the appropriate emergency response, as well as influence interim and permanent solutions. For the purposes of this article, we will focus on two general types of seepage exit characteristics: concentrated versus disperse seepage. For those readers familiar, this is not to be confused with terminology conventions of internal erosion mechanisms (concentrated leak erosion, backward erosion piping, contact erosion, etc.). "Concentrated" versus "disperse" seepage in this context is simply a descriptor related to the relative discreteness of the identified seepage exit. Concentrated flows are those that have a distinct, identifiable exit over a relatively small area. Some signs of concentrated seepage exit flows are rupture or blow out at an isolated area near the toe of the dam, seepage around a contact or conduit penetration, a sand boil or set of adjacent sand boils, or identifiable points of pluming or sediment deposition. Conversely, disperse seepage is that which covers a broad area, as shown in Figure 1.

Figure 1. Disperse Seepage at Dam Toe (Wyoming NRCS)

Actions to consider and implement – and what not to do

Potential intervention actions to control concentrated seepage until more permanent repairs can be made are described below. It is important to stay flexible and respond to conditions as they develop; don't get overly attached to any given approach.

Conventional Filter Blanket. Where seepage is dispersed and discharging at relatively low velocity a conventional filter blanket comprised of sand (e.g., ASTM C33 fine aggregate) can be placed directly over the area of seepage to trap fine eroded soil entrained in the seepage flow, and allow the clarified seepage water to pass freely downstream. Filter-compatible gravel would typically be placed over the sand blanket, acting as a drain and protective ballast (see Figures 2a and 2b). That ideal, however, is rarely achieved in the case of concentrated seepage flow. Filter sand itself is highly erodible under even moderate flows. If the flow from a concentrated seep is strong enough, it may not be possible to place a thick enough cover of filter sand (or even gravel) quickly enough to prevent it from washing away. And, if the filter sand cover is too thick, the risk of impeding sufficient drainage through the filter increases. To combat these conditions, the concept of an "inverted filter" should be considered as discussed next.

Figures 2a and 2b. Conventional Filter Construction: Placing Sand Filter (Left) and Ballasting With Gravel (Right) at Bureau of Reclamation Dam [2].

Inverted Filter Blanket. An "inverted filter" (sometimes referred to as a "reverse filter") should be considered where the concentrated seepage discharge rate, and by extension the head within the dam or foundation driving the discharge, are already higher than can be controlled by a conventional sand filter blanket or another direct discharge intervention (e.g., a "sandbag ring" as discussed below).

With this intervention, rather than first placing erodible filter sand, a material with a coarser gradation is placed as a diffuser to lower the velocity of the concentrated seepage at the exit point so that the filter sand can be placed without washing away. The coarser material must be heavy enough not to be washed away by the seepage flow, sufficiently permeable to pass the flow at lower velocity but still relatively freely, and not so open-graded that the filter sand will be at risk of falling into the rock and being washed away. A judgment will have to be made as to what material to use as the diffuser zone of the inverted filter based on local, timely availability, as well as design considerations. It may be that more than one coarse layer will have to be considered in the diffuser zone.

Once the lower coarse layer (diffuser) is in place, the overlying filter sand (as described above under Conventional Filter Blanket) can be placed, fully enveloping the diffuser layer. The filter zone prevents (or at least minimizes) escape of the internally eroding soil, while still allowing relatively free passage of the seepage water. If the filter is too fine and its permeability too low, there is a risk that the seepage flow that is currently freely discharging will back up behind the filter.

Figure 3. Inverted Filter Berm at Salt Fork Dam [4].

The ballast/drain material is typically gravel (sometimes up to small cobble sizes) that protects the filter from external damage (erosion from wind and rain and equipment access/passage where required). This zone also serves as a drain, allowing the seepage flow to escape freely downstream. If the lower coarse (diffuser) zone and filter material function as intended the filter compatibility of the filter and ballast/drain may not be critical, but this condition must be evaluated. Figure 3 shows a completed inverted filter blanket controlling an area of concentrated seepage.

> *Unintentionally choking seepage discharge could result in locally high gradients that may well induce internal erosion in another area(s), or possibly lead to a slope failure on the downstream face of the dam due to saturation and increased, uncontrolled pore pressures in the downstream embankment fill.*

Figures 4a and 4b show conceptual designs of an inverted filter for concentrated flow from a sinkhole and from surface seepage discharge at or beyond the toe of the dam. If possible, grade the base of the filter system to direct as much seepage as practical to a common discharge at the downstream side of the system, and install a weir to monitor discharge from the concentrated seep (see, for example, the case study of Needwood Dam at the end of this article).

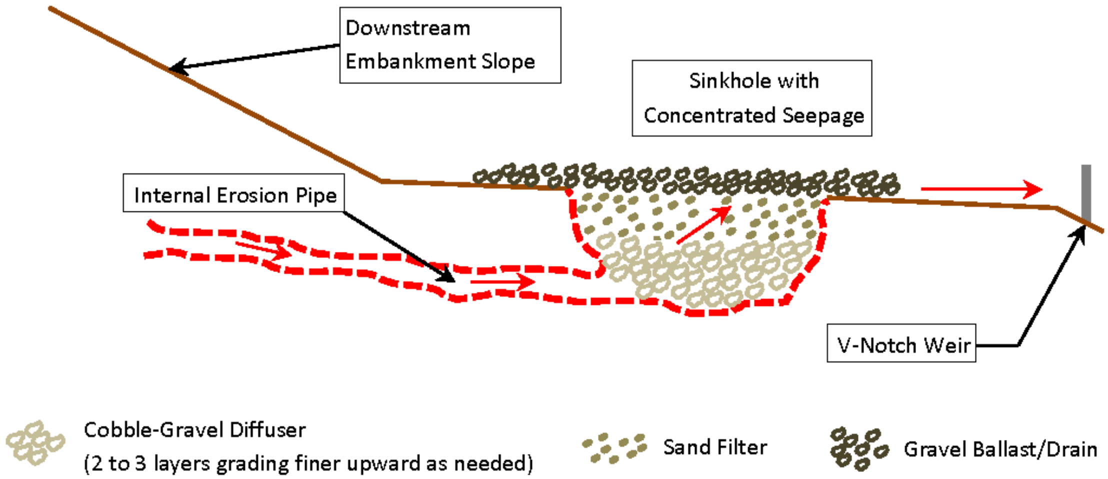


Figure 4a. Conceptual Design of an Inverted Filter (Concentrated Seepage).

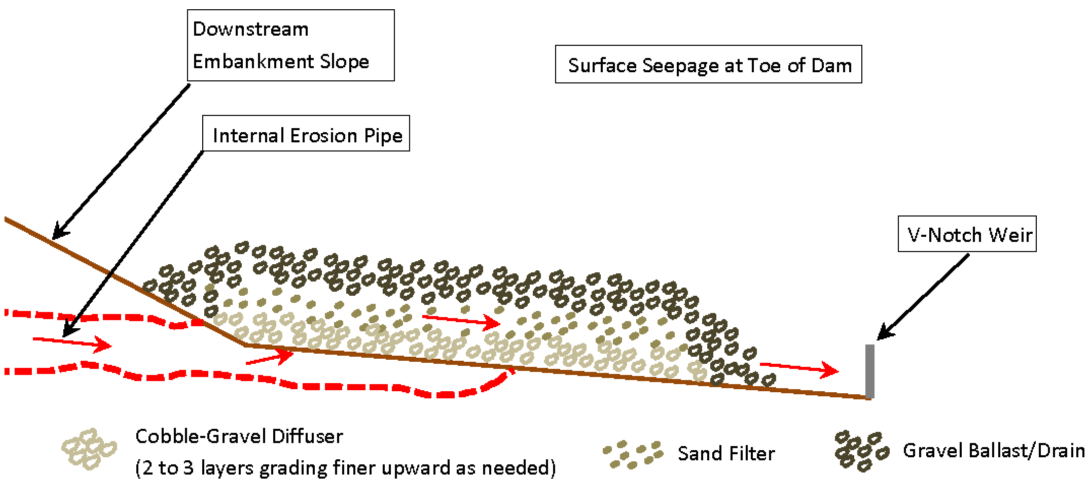


Figure 4b. Conceptual Design of an Inverted Filter (Disperse Seepage).

An alternative approach to consider at a concentrated seep is the use of geotextile as the filter material in place of sand (see Lake Needwood Dam case history below). With this intervention, the geotextile material would be deployed either directly over the area of concentrated seepage or on an initial layer of coarse (preferably not too angular) gravel. Deployment would ideally begin well upslope of the area of active seepage as protection against enlargement of the area of seepage over time. Also, deployment would be easier and safer using gravity where possible to roll out the material. As the geotextile is deployed it should be initially ballasted with sand bags at close enough spacing to counteract any tendency for billowing and lifting due either to the concentrated flow or wind. The placement of the sand bags would follow immediately along with the deployment. If ground conditions and accessibility allow, the sand bags may be deployed manually; otherwise a hydraulic excavator or other equipment with suitable reach may be used. Immediately following or together with the deployment of the geotextile and sand bags, a layer of gravel should be placed over the fabric to more uniformly ballast the geotextile, while not impeding free drainage from the geotextile.

One potential concern with the use of geotextile as the filter is that it tends to clog more readily than a properly designed earthen (i.e., sand) filter. If possible, a non-woven geotextile with the greatest apparent opening size (AOS) should be used to enhance permeability of the filter. This clogging factor will have to be balanced against the potential loss of more eroded fines than ideal. Another factor to consider is the timely shipping of a suitable geotextile to the site. In rural areas, typical concrete aggregates may be found more readily in the vicinity than geotextile. If more readily available, a woven geotextile (often used for silt fence) can be considered (good permeability, but less efficient filtering of fines). It may be appropriate to use the geotextile as a temporary emergency measure until a more robust engineered filter can be constructed as a permanent repair.

Depending on the ready availability of either geotextile or aggregates, it may be prudent to pre-order and store on-site appropriate materials to provide more immediate response if a seepage event were to occur. This is especially true if there is a suspected seepage deficiency at the site.

Other considerations in the construction of an aggregate or geotextile filter system include, but are not necessarily limited to the following:

- *Availability of equipment (haul trucks, tracked excavator, dozer and/or loader; portable light plant, etc.); consider equipment that may already be on-site or may be readily available from neighbors, highway department maintenance facilities, federal agencies (e.g., the U.S. Forest Service for dams on or near USFS lands), etc.*
- *Inducing detrimental loadings (avoid equipment, to the extent feasible, with high concentrated tire or track loads to minimize bearing failures, and equipment producing strong ground vibrations to minimize potential liquefaction of susceptible saturated materials).*
- *Site conditions (if seepage has resulted in extremely soft ground conditions, it may be necessary to mobilize low ground pressure [LGP] equipment and/or a long reach hydraulic tracked excavator [e.g., Cat 324DL, PC220-2, etc.]).*
- *Under the most extreme site access conditions it may be necessary to employ a helicopter to transport mini-equipment and materials, and possibly to place the materials, if equipment access is not feasible.*

In some instances concentrated seepage occurring immediately at the downstream toe, or worse on the lower downstream slope, can result in severe erosion that may eventually undermine the slope and result in local or progressively larger slope failure. If such a condition is, already has, or may occur, then placing an earthen stability berm is warranted (see AV Watkins and Washakie Dams case histories below). If erosion and slumping or sliding is limited in the immediate vicinity of the concentrated seepage and does not appear to be progressing further upslope or laterally, then frequent and diligent monitoring can be implemented and used as the basis for determining if or when a berm is required. Often once the active seepage is controlled, the local erosion and instability around the seep ceases.

Diverting Inflow to the Reservoir. If inflow to the reservoir includes flow conveyed by a canal or natural drainage with a controlled diversion or inlet structure or a waste-way that could be utilized to divert that flow from entering the reservoir, such a measure should be considered early during the incident. One key consideration in making the decision where this action is technically feasible is whether other potential damaging impacts may occur downstream in the drainage to which flows are diverted.

Lowering the Reservoir Pool. The first action to be considered in the event of a serious or visibly worsening seepage discharge is lowering the reservoir pool. This should be implemented as soon as possible and at the maximum drawdown rate possible. The sustained drawdown rate implemented should consider what rate may result in slumping, damage, and instability of the upstream slope due to pore pressures in the embankment that are not able to drain (i.e., rapid drawdown failure), and temper that with consideration of the urgency of the seepage incident. Lowering can always be slowed or stopped if the concentrated seepage is determined not to be a threat to the dam or is stabilized by response actions. Most commonly, reservoir lowering will be by discharge through a low-level outlet conduit. However, if the dam has a gated spillway, opening the spillway gates should be considered. It is important to provide warning to downstream population and emergency managers prior to significantly increasing outlet and/or spillway releases. Consideration can also be given to supplementing the drawdown rate with siphons or pumps.

Fill Sinkholes/Entry Points. Depending on seepage velocity, a downstream filter blanket alone may be insufficient to stop the internal erosion of soil caused by concentrated seepage. If the condition assessment identifies specific locations where reservoir water is entering the dam, abutments, or foundation, consideration should be given to slowing or stopping flow into the entry. It is important to understand; however, that this is often a challenging and sometimes unsuccessful emergency intervention. This approach might be successful where a clearly identified entry point (i.e., a sinkhole or whirlpool) is close to the dam or reservoir rim in an area that is or could be made accessible without extraordinary effort (see Figure 5). The objective of at least partially plugging the open entrance is to slow (and if possible effectively stop) the entry of reservoir water and thereby reduce or stop the downstream concentrated seepage and associated internal erosion. However, there are many examples of situations where blocking upstream sinkholes with a blanket do nothing more than cause the sinkhole to move. Materials that might be used depending on availability, access, equipment and labor to deploy them include: heavy gage sheeting (e.g., geomembrane, geotextile, reinforced plastic tarp, etc.) weighted down by sufficiently large rock (coarse gravel, cobbles and/or small boulders); the large rock without the sheeting (preferably a mix of sizes to minimize large voids); large sand or gravel filled geosynthetic bags; hay bales weighted with concrete blocks; concrete blocks or demolition debris; or random, low permeability fill that effectively increases the length of the seepage path. The material would likely be deployed by a tracked hydraulic excavator (ideally with extended reach capability), a crane and bucket, or in the direst of circumstances by a helicopter and bucket. If there is available time, other options may be considered, such as grouting or placement of a layered backfill, as shown in the Western Dam Tech Notes article "Sinkholes: The Hole Story…Issues are Deeper than you Think".

Figure 5. An Accessible Sinkhole in the Early Stages of Development – a Good Target for Plugging

If reservoir water is entering in a large and/or diffuse area (e.g., through fractures in an extensive bedrock unit), measures to address such a condition while the reservoir is full (or is at least submerging the problem area) are limited. However, consideration should be given to placement of an upstream "choke filter" to slow the entrance of reservoir water and thereby slow the seepage discharge downstream. The choke filter comprises sand and gravel and is placed as a berm over the area of seepage entry. The filter material can be placed through shallow water by dozing from the shoreline, or more ideally as the reservoir pool is being drawn down. The Bureau of Reclamation successfully employed this technique at AV Watkins and Deer Flat Dams.

Figure 6. A Placement of Upstream Berm at AV Watkins Dam [4].

Place "Sandbag Ring" at Discrete Point(s) of Seepage Discharge. In cases where discrete concentrated seepage at a still manageable (i.e., relatively low) flow rate is exiting the downstream slope, toe area, or abutment(s) of the dam, "sandbag rings" have often proven effective as a response action (see Figure 7). The objective of a sandbag ring is to create a back-pressure head on the seepage discharge that is sufficient to slow the flow but not so much as to block or over-pressurize the seepage and cause it to divert to another flow path(s) and perhaps do more harm than good. It is important to provide an overflow to safely convey the reduced seepage flow from the ring and then downstream, and a means to measure the head within the ring and the discharge flow rate. Sufficiently frequent measurements of head and flow should be made until a reasonably steady state condition is achieved, or a condition of reducing head and flow that is commensurate with reservoir lowering, if implemented. Note that using sand bags is often the most efficient and rapid means to achieve the back-pressure pool desired. However, other materials can and should be used if more readily available and suitable to site conditions. This might include constructing a berm with: compacted clay, common soil, or aggregate lined with plastic sheeting or geomembrane; concrete blocks wrapped in tarp and stacked in a stable manner; or some other practical means.

Figure 7. A Sandbag Ring with V-Notch Weir [4].

Internal Erosion along a Conduit. An especially challenging condition of concentrated seepage is uncontrolled flow from around a conduit through the dam or foundation. As seen in Figure 8, this can lead to severe consequences. In concept, the measures described above for an inverted filter using either aggregate materials or geotextile still apply to addressing this condition. The major challenges in this case are typically associated with seepage along an actively discharging outlet conduit. These challenges include access to the area of discharge and placing materials. As a result, it may prove more feasible to utilize geotextile as the filter material. Regardless of the material used, it is strongly recommended that the filter protection be placed around the full circumference of the conduit for at least several diameters beyond. This will provide protection in the event that additional erosion occurs around the pipe or the existing seepage moves in response to the placement of the filter system.

Figure 8. Seepage Along a Conduit Led to Dam Breach (Courtesy of Wyoming State Engineer's Office).

Another intervention to consider is placing a dike with an armored overflow below the discharge end of the conduit to impound a pool that would submerge the area of concentrated seepage discharge while still allowing free discharge of the seepage and, in the case of the outlet works conduit, emergency releases from the reservoir. The intent of this approach is to mimic the effect of a sandbag ring as described previously. The dike would be most readily constructed with large rock (e.g., riprap); seepage through the dike would be minimized by placing progressively finer earth material, reinforced plastic tarp, or some other suitable seepage barrier on the upstream slope and basin floor. If appropriate to site conditions, dike constructability, and outlet operational needs or flexibility, the outlet conduit could be extended through the dike. In that configuration, the pool behind the dike would be filled by the concentrated seepage discharge, supplemented, if necessary, by pumping or siphoning from the channel below the dike to make up for unavoidable seepage losses through or under the dike.

Case Histories

AV Watkins Dam [5]

The event:

- *Concentrated seep discharging 1-2 cfs (500-1000 gpm)*
- *Sand boils w/cloudy discharge – active piping (internal erosion)*
- *Significant sediment deposition in downstream toe ditch*
- *Sloughing/cracking of downstream slope*

The intervention:

- *Initial attempt to place sand filter material fails – sand washes away*
- *Thick filter and stability berm placed over seeps – still 100-200 gpm cloudy seepage in South Drain*
- *Large berm constructed at upstream sinkholes (seepage entrances) to reduce downstream seepage discharge*

Lake Needwood Dam [4]

The event:

- *Concentrated seep in left downstream groin about 4 to 6 inches in diameter; later measured at 80 gpm as reservoir was lowering)*
- *Entrained sediment noted in 'styrofoam coffee cup test' – active piping (internal erosion)*
- *Piezometers show significant rise of phreatic surface in dam – concern for downstream slope stability*
- *Toe area of dam very spongy – high uplift pressure*

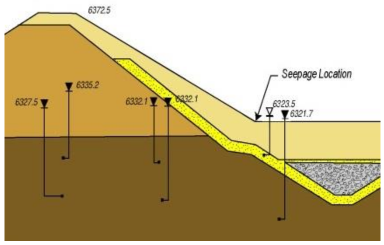
The intervention:

- *Maximum outlet works discharge implemented*
- *Use of inverted filter approach*
- *Initial attempt to place gravel as coarse filter material to reduce discharge velocity fails – gravel washing away*
- *Then used geotextile as filter, ballasted by sandbags and gravel*
- *Gravel ballast 5-6 feet thick required to control discharge while reservoir pool was lowered*

Washakie Dam [4]

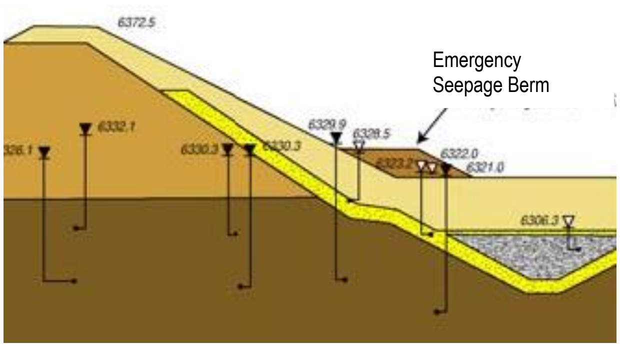
The event:

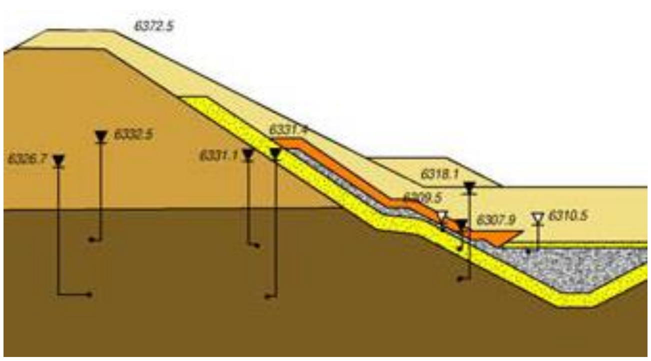
- *Unexplained, persisting wet area on new stability berm upon refilling reservoir; high piezometer readings within new chimney filter*
- *Upon refilling the reservoir after the new berm construction, a wet area was observed and test pit excavated to investigate*
- *Concentrated seepage flow > 80 gpm and appearing to increase entering bottom of shallow test pit*
- *Entrained sediment observed in seepage flow into the test pit – active piping (internal erosion)*



The intervention:

- *Outlet gates immediately fully opened*
- *Use of inverted filter approach*
- *Backfilled test pit with sand and gravel already stockpiled on site due to historic seepage issues*
- *Mounded filter sand over sand and gravel to 6 feet above original grade to mitigate seepage reappearing at top of filter*
- *Full-time surveillance overnight until seepage stabilizes at about 1 gpm by late morning*
- *Permanent solution included constructing a gravel chimney drain downstream of chimney filter to prevent surcharging of the chimney filter*





Lessons Learned and Recommendations

Key points to keep in mind in preparation for and when faced with a concentrated seepage event include:

- Consider developing an Emergency Intervention Plan to identify preparedness actions in advance.
- Stay calm; panic does no one any good.
- Assess conditions quickly, but accurately, and update as appropriate.
- Choose intervention actions carefully, with as much awareness as possible of the potential downsides of those actions.
- Reduce seepage exit velocity first with a diffuser, and then address controlling piping (internal erosion) with a filter.
- Availability of materials and equipment in an emergency can make the difference between a close call and a dam failure.

A functional outlet works with good discharge capacity is very valuable; consider immediately lowering the reservoir pool.

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Calibration, Validation, and Verification: Bringing More Certainty to the Uncertainty of Hydrologic Modeling Results

Introduction

Engineers and regulators alike are frequently confronted with the task of attempting to accurately simulate and estimate processes that are both highly complex and variable. The dam safety arena is no different in this respect, particularly as it applies to the "black magic" better known as hydrologic watershed modeling. The hydrologic responses of a watershed are dependent on sundry variables—all of which are difficult to confidently and accurately estimate—and when combined, do not usually give one a warm and fuzzy feeling of confidence. For this reason, hydrologic modeling for dam safety evaluations is often performed using conservative methodologies.

While a conservative approach helps us all to sleep a little easier at night, it can significantly increase hydrologic model runoff results and associated dam flood passage infrastructure requirements. This of course can lead to costly dam modifications, which may or may not be entirely necessary based on the level of conservatism adopted as part of the modeling.

Wouldn't it be nice to be able to justify and verify that the parameters and approaches adopted as part of hydrologic watershed modeling are accurate and appropriate? Of course it would—and you can (well, sort of). A model verification process can be employed to provide degrees of confidence and reliability in modeling results ranging from very high to very low, but hey, very low is better than extremely low or zero! More often than not, though, it is likely that model result confidence and reliability will lie somewhere between these extremes; but, like most applications to engineering evaluations, available data quantity and quality is extremely influential and important.

The model verification process [1, 2] is summarized on Figure 1. The goal of a verified hydrologic model is to be able to adequately replicate observed, measured, and predicted watershed data, like runoff rates and volumes, for a suite of events, conditions and scenarios. This is accomplished through a process of:

- Using a hydrologic model to estimate runoff;
- Comparing modeled runoff estimates to available watershed data to assess the adequacy of the results; and
- Adjusting and refining model watershed input parameters to improve agreement between modeled runoff and available watershed data for a suite of events, conditions and scenarios.

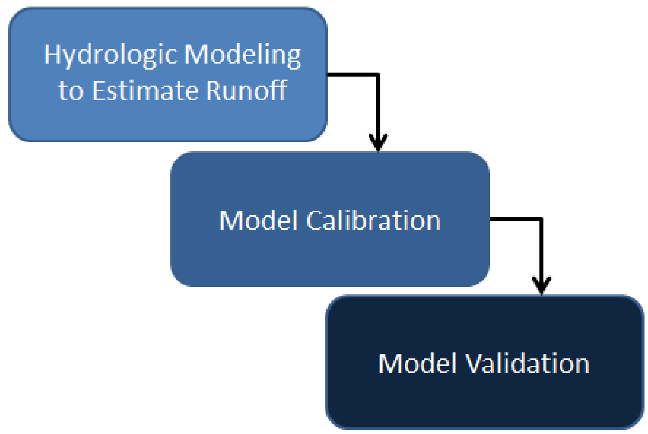

Figure 1. Watershed Hydrologic Model Verification Process.

A verified hydrologic model can be used to confidently predict the watershed responses resulting from a range of precipitation and flood events; however, reliable return intervals often fall within a range more frequent than a 500-year return period due to available data limitations. For this reason, it can be more difficult to verify hydrologic models for dams with higher hazard potentials as the inflow design floods (IDF) are often significantly less frequent than a 500-year event.

Runoff Estimation – A Quick Review

This article builds on previous Western Dam Engineering Technical Note (WDETN) articles—one of which focuses entirely on the [process of estimating runoff though flood modeling [3]](). Rather than referring the reader to that article alone, let's quickly review the steps required to transform precipitation to runoff.

<u>Step 1:</u> Define the precipitation and corresponding IDF event

- For the purposes of dam safety, the IDF is the flood event required to be safely routed through the reservoir. The IDF is typically based on a dam's hazard classification and can be defined with return periods ranging from a 50-year event to extreme events with return periods less frequent than a 1,000-year event (like the probable maximum flood [PMF]).

Step 2: Develop the IDF storm hyetograph

- Estimate a depth-duration-frequency relationship (from local precipitation gages, gage-adjusted radar rainfall data, NOAA Atlases, Hydrometeorological Reports [HMRs], Site-Specific or Statewide Probable Maximum Precipitation [PMP] studies, etc.)
- Estimate areal reductions (if applicable).
- Estimate elevation reductions (if applicable).
- Estimate spatial and temporal distributions.

Step 3: Estimate watershed loss parameters and excess precipitation

- The most pertinent watershed loss parameters (as they relate to dam safety) are surface retention (initial losses) and infiltration.
- Some common methodologies to estimate these loss parameters include: Green and Ampt, Natural Resources Conservation Service (NRCS) Curve Number, and Initial and Constant Loss.

Step 4: Transform watershed excess precipitation to discharge hydrographs

- Excess precipitation (i.e., runoff) is translated to discharge hydrographs using a translation methodology—the unit hydrograph is generally the most preferred and is based on physical watershed properties and associated flood travel times.
- Some common methodologies to estimate unit hydrographs include:
  - Watershed-Specific Unit Hydrographs – Use watershed precipitation and stream discharge data.
  - Synthetic Unit Hydrographs – Where insufficient watershed data is available, common methodologies include those of the U.S. Bureau of Reclamation, NRCS, Clark, and the U. S. Geological Survey (USGS).

Step 5: Estimate watershed runoff volumes and hydrographs

- Use a hydrologic model, like HEC-HMS, and the data estimated in the previous steps to estimate peak runoff rates and volumes.
- If applicable, combine and route sub-watershed hydrographs through the watershed drainage network watercourses. Some common watercourse routing methodologies include: Kinematic Wave, Muskingum-Cunge, Lag, and Modified Puls.

So that's runoff in a nutshell—the reader is encouraged to reference the WDETN runoff article [3] for a more detailed discussion. But how do we know if the flood modeling runoff results are reasonable and reliable? This is where a variety of calibration and validation techniques and methodologies can be applied to justify and refine results and the input parameters that contribute to them.

Watershed Model Calibrations

General Discussion and Overview

Model calibrations comprise adjustments to model input watershed parameters such that model results closely approximate observed or predicted data. Watershed parameters are initially estimated and adopted based on the methodologies and techniques discussed in the previous runoff review section (as well as in the WDETN runoff article [3]). Although these methodologies are reflective of industry standards and state of the practice, they typically require adjustments to produce reasonably accurate results.

Figure 2 presents an example in which the modeled runoff volume, time to peak discharge, and the peak discharge do not reasonably replicate measured discharge data, which could indicate that the model results are inaccurate and/or questionable. To justify selection of adopted hydrologic model input parameters and verify associated model runoff results, model calibrations and validations are necessary.

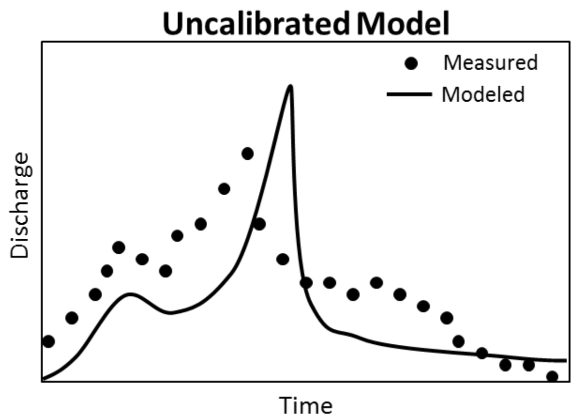

Figure 2. Unacceptable Simulation from an Unverified Model.

Figure 3 presents an example in which the modeled runoff (from Figure 2) has been calibrated and has a high degree of accuracy and reliability.

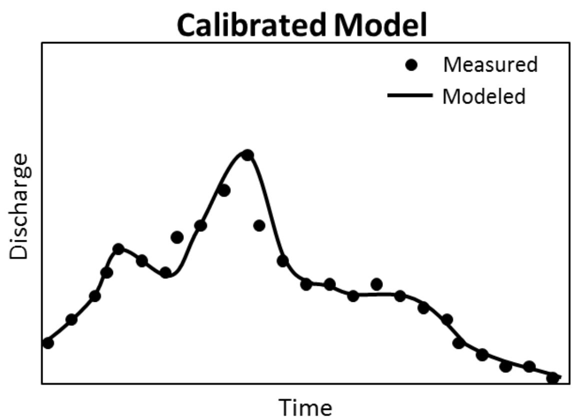

Figure 3. Acceptable Simulation from a Verified Model.

The *Extreme Storm Working Group Summary Report* (MT ESWG) prepared by DOWL in December 2016 for the Montana Dam Safety Program (Department of Natural Resources and Conservation) provided an excellent overview of model verification and calibration techniques and methodologies [4]. As described by the MT ESWG, model simulation calibrations are based on two general methodologies:

1) Calibration – The process in which the parameters of a hydrologic model are adjusted to replicate a measured or observed event (gaged watersheds). Gaged data include those from precipitation, snowpack, and stream discharge gages. This process lends itself to a high degree of confidence and reliability.
2) Pseudo-Calibration – The process in which the parameters of a hydrologic model are adjusted to reasonably approximate a range of flood frequency values obtained independently from the hydrologic model, such as the 100- and 500-year events (gaged and ungaged watersheds). Ungaged data include those from local and regional regression equations (e.g., USGS regional regression for peak runoff rates) and correlations with similar, neighboring gaged watersheds. This process lends itself to more of a “sanity check”.

Ideally, a calibration to a single or series of measured or observed events can be performed for a given watershed. Unfortunately, most watersheds lack sufficient data to perform a calibration due to:

- No measured or observed data;
- Generally short or incomplete data records and associated statistical limitations (i.e., attempting to reliably estimate infrequent event data based on a small sample size); and
- An absence of observed infrequent precipitation, snowpack/melt, and stream discharge event data.

For these reasons, pseudo-calibrations are often necessary to verify flood modeling runoff results; however, the use of measured or observed data for pseudo-calibrations is often met with the same limitations described for calibrations. As such, pseudo-calibrations are commonly performed using data that are generally regional and not specific to the watershed. This can be accomplished by using regression equations developed by organizations like the USGS (https://water.usgs.gov/osw/streamstats/) or USACE, as well as those developed based on Log Pearson III or other probabilistic comparisons for neighboring and similar watersheds, in which, more robust observed data are available.

Neighboring and similar watersheds could include those that are adjacent to the study watershed or lie within the same overall hydrologic basin and have similar watershed characteristics like area, elevation, shape, topography, vegetative cover and general precipitation loss parameters. By “normalizing” these characteristics and parameters, a comparison of runoff rates per area (e.g., cfs per acre) can be estimated for a range of events and conditions and can be used as part of study watershed pseudo-calibrations.

Due to the regional nature of some pseudo-calibration data, calibrations may not be able to adequately replicate predicted runoff rates; however, general discharge-frequency tendencies should be retained, if possible, which provides some degree of reliability and confidence. Figure 4 shows an example in which the modeled discharge frequencies do not have the same tendency as the observed data and do not lie within the 90 percent confidence band. Ideally, a verified model (Figure 5) should produce results that retain the same tendency as observed or predicted data and lie close to the line of equal values.

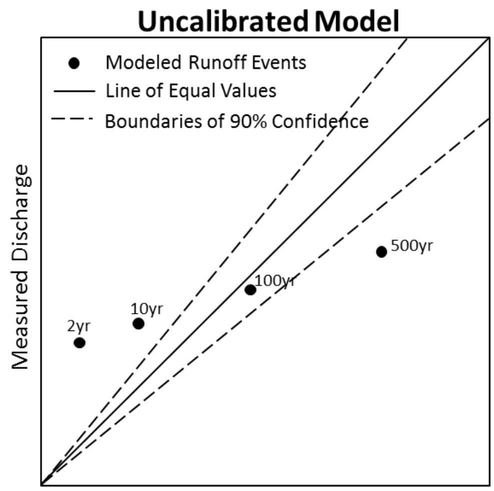

Figure 4. Unacceptable Simulation for an Uncalibrated Model.

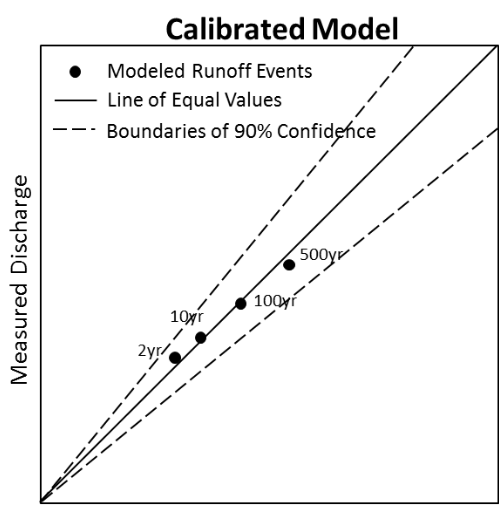

Figure 5. Acceptable Simulation from a Calibrated Model.

Flood modeling runoff result verifications are often focused on replicating peak runoff rates; however, in some cases, the runoff volume can prove to be more critical than the peak runoff rate. Runoff volume verifications require measured or observed event data; therefore, these types of verifications are calibration based. Conversely, peak runoff rate verifications can be based on watershed specific and/or regional data and associated calibrations and/or pseudo-calibrations.

Calibration Techniques

Hydrologic model runoff result calibrations involve varying estimated watershed input parameters such that the model results match well with observed and/or estimated data under similar conditions. It is important to note that model input parameters are generally adopted based on methodologies and empirical relationships whose own parameters are subject to interpretation and engineering judgement.

As such, a range of potentially reasonable values/magnitudes for a given watershed parameter is expected and appropriate. These ranges provide a basis (i.e., upper and lower limit) for which model input parameters can be varied and justified.

Figure 6 presents a flow chart of a typical hydrologic model runoff result calibration process. Common watershed input parameters varied as part of this process include:

- Excess precipitation – Infiltration, evaporation, and transpiration rates, as well as initial abstraction (i.e., interception). Initial abstraction and the infiltration rate are the most pertinent to dam safety studies.
    - Runoff volume modeling results are most sensitive to watershed loss and excess precipitation parameters.
- Excess precipitation transformation – Physical watershed characteristics like shape, topography, surface roughness, etc.
    - Runoff rates and timing are most sensitive to excess precipitation transformation parameters.
- Watercourse routing – Physical watercourse characteristics like hydraulic roughness, slope, cross-sectional geometry, etc.

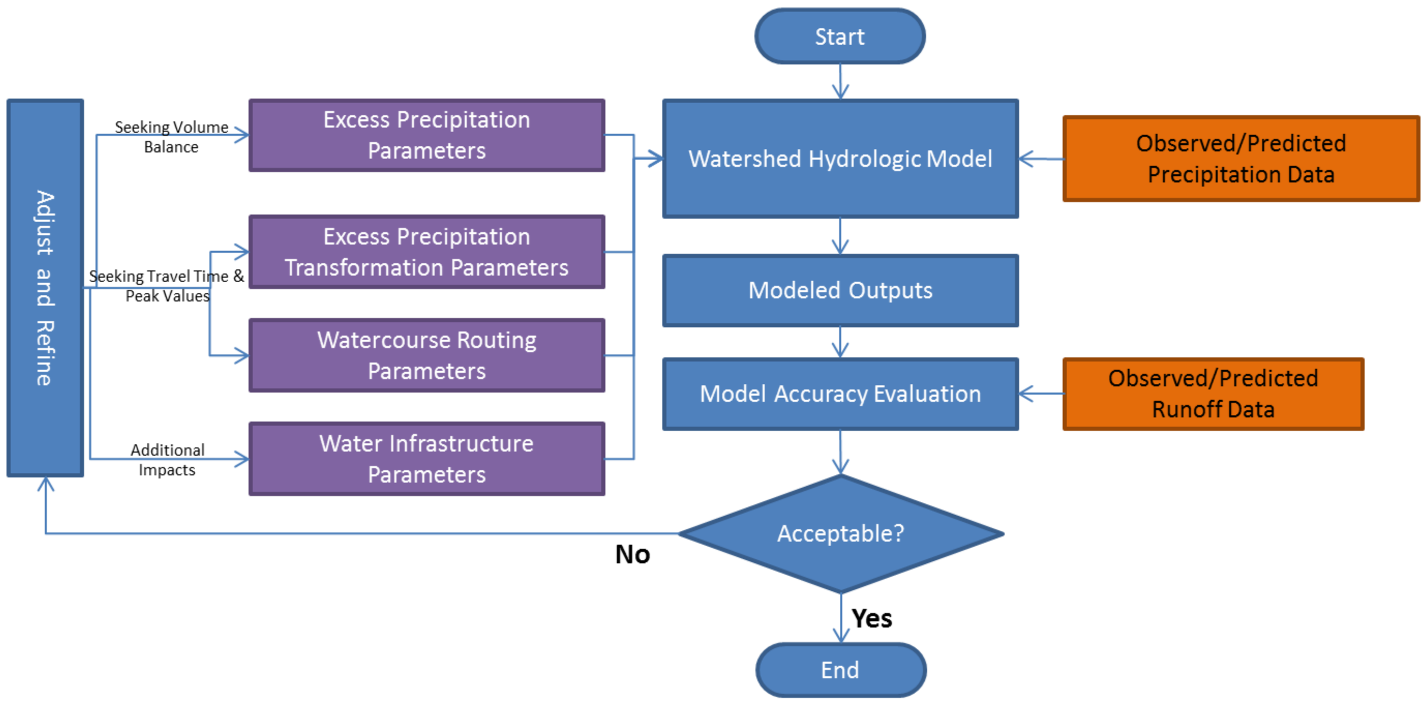

Figure 6. Hydrologic Model Calibration Process

  - Runoff rates and timing are most sensitive to watercourse routing parameters.
- Water infrastructure – Water infrastructure (i.e. diversions, reservoirs, etc.) and their operational strategies can significantly alter watershed runoff volumes, rates and timing and may need to be considered as part of a calibration process.

It should also be noted that stochastic methodologies and simulations, like Monte Carlo, are becoming more common and accessible for hydrologic evaluations associated with dams. These evaluations produce and model a suite of simulations (on the order of thousands) by varying input parameters based on specified probabilities of occurrence within a reasonable range of potential values. The results of these simulations provide confidence intervals for parameters of interest (e.g., peak runoff rate, etc.), which can be an extremely useful part of verification and calibration evaluations.

Ultimately, the purpose of a verification and associated calibration process is to provide a reasonable and appropriate model for a range of conditions. As such, hydrologic models should not be calibrated to agree exceedingly well with only a single condition or scenario, as this could render the model unacceptable and/or inappropriate for other conditions or scenarios. For this reason, model validations are performed to provide a basis for adjusting and testing calibrated models for additional conditions and scenarios.

Model Validation and Verification

General Discussion and Overview

Model validations are evaluated based on an initially calibrated model and comparisons between model results and observed or estimated data resulting from independent or additional conditions and scenarios. For example, the gage discharge data shown in Figure 7 represent a time series record. The entire record is not used as part of initial model calibrations so that a portion of the data set can be "set aside" and used to independently validate model results for the initially calibrated model. These "independent" data sets differ based on available data and the nature of corresponding calibrations:

- Calibrations – Independent data are based on measured or observed (i.e., gage) data and could include additional individual precipitation or stream discharge events, derived frequency events (using the full record of gage data), etc. Other methodologies, like those associated with ungaged watersheds (e.g., regional regression equations to predict runoff rates), could also be used; however, observed and measured data are preferable, where available.

- Pseudo-Calibrations – Independent data are based on both observed (i.e., gage) and predicted (i.e., ungaged) data and could include the aforementioned independent gage data as well as runoff rates predicted from local and regional regression equations, correlations with neighboring gaged watersheds, etc.

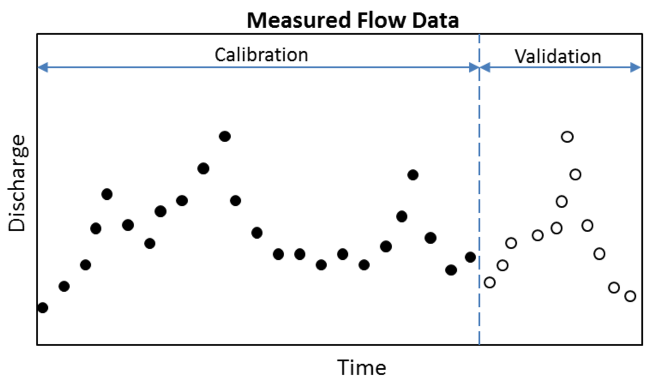

Figure 7. Gaged Discharge Time Series Used for Model Calibration and Validation.

Model Validation

Figure 8 presents a flow chart of a typical model runoff result validation process. This process is similar to that of the calibration process with the exception of the data used to perform the validation, which is independent of that used as part of the calibration process.

One can see that the calibration, validation, and overall verification process is iterative in nature—the model is calibrated for one condition or scenario and then initially verified prior to being evaluated for additional conditions and scenarios and further verified. If you cross your fingers and toes while holding a four-leaf clover, you may only have to go through the whole process once, but more likely than not, a series of refinements and adjustments will be required to produce a model that is fully verified across a suite of conditions and scenarios. Just remember, verification is valid when validation is verified!

But what constitutes an adequately verified model? Model accuracy evaluations are performed and provide a basis for satisfactory agreement between observed or predicted data and modeled result data.

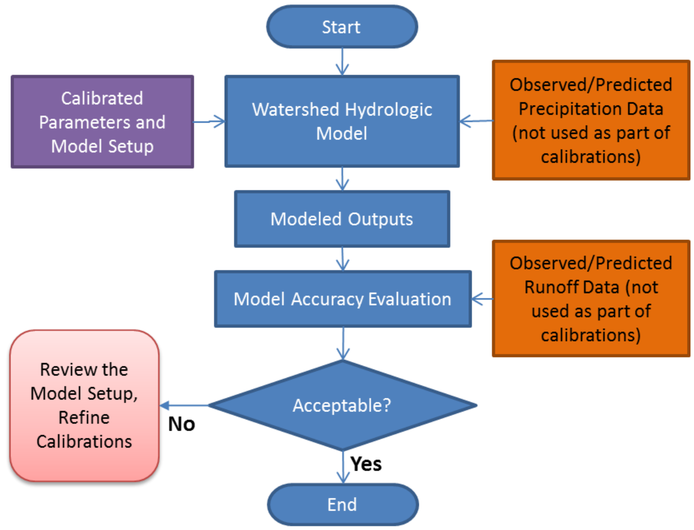

Figure 8. Hydrologic Model Validation Process.

Model Accuracy Evaluations

Model accuracy is frequently evaluated by statistical comparison of measured or predicted data and modeled results [5]:

1. Percent Bias Coefficient (B_p),

$$B_p(\%) = 100 \cdot \sum_{i=1}^{n} \left(\frac{O_i - C_i}{O_i} \right)$$

Where: n= number of pairs of the observed and modeled variables; O_i= observed data; and C_i= modeled value. The B_p is expressed as a percentage and describes the tendency of the modeled data to be greater or smaller than the observed data. The corresponding accuracy classification is:

$B_p \leq \pm 10$	Very good
$\pm 10 < B_p \leq \pm 15$	Good
$\pm 15 < B_p \leq \pm 25$	Satisfactory
$B_p \geq \pm 25$	Unsatisfactory

2. Nash-Sutcliffe Coefficient (N_s),

$$N_s = 1 - \sum_{i=1}^{n} \left[\frac{(O_i - C_i)^2}{(O_i - \bar{O})^2} \right]$$

Where: $\bar{O}$= mean of observed data. The N_s describes the deviation from unity of the ratio of the square of difference between the observed and modeled values and the variance of the observations. The corresponding accuracy classification is:

$0.75 < N_s \leq 1.00$	Very good
$0.65 < N_s \leq 0.75$	Good
$0.50 < N_s \leq 0.65$	Satisfactory
$0.40 < N_s \leq 0.50$	Acceptable
$N_s \leq 0.40$	Unsatisfactory

A model is considered verified and appropriate for use for a range of conditions and scenarios with a classification ranging between very good and satisfactory for both of these statistical comparisons.

Additionally, the MT ESWG suggests that a model can be considered verified if its results are within one to two standard deviations from observed or predicted data.

Common Questions and Additional Advice

Hydrologic model verifications require that an engineer juggles a collection of interdependent data, which can become complex and onerous work. While developing a fully verified model can be a daunting task, we're here to help! Here are a few common questions and answers to guide you through the process:

Q1: Can a calibrated model based on measured data from a single storm event be utilized for other storm event simulations?

Answer/Suggestion: Yes, provided that antecedent and initial conditions are similar between the two events.

Q2: I was able to achieve satisfactory model accuracy; however, a channel Manning's n value of 0.005 was adopted during the calibration process. Can I consider my model to be verified and reasonable?

Answer/Suggestion: No, the adopted Manning's n value falls well outside the range of expected and reasonable values. All model watershed input parameters must fall within a reasonable range of values when being varied as part of a calibration process.

Q3: No extreme storm events, like the PMP, were observed or measured in my project watershed. How can I develop an applicable hydrologic model for an IDF based on an extreme flood event like the PMF?

Answer/Suggestion: Generally, an infrequent event with a return period frequency of 100 years or less can be used to calibrate a hydrologic model for extreme events. As such, a model calibrated from gaged data that corresponds to 100-year, 200-year and 500-year events should be suitable for a PMP hydrologic simulation. If gage data are not available for these infrequent events, a pseudo-calibration utilizing local and regional regression equations is recommended.

Q4: How often should I review and recalibrate a hydrologic model?

Answer/Suggestion: Model review is recommended when the following occur:

- Significant precipitation and/or flood events have occurred within the project watershed and/or the region. New data should be used to revalidate the model. If model accuracy is unsatisfactory based on the revalidation process, the model should be recalibrated.
- Watershed conditions have changed (e.g., new development, wildfire, etc.). In this case, the model accuracy should be reviewed and the model should be recalibrated, if necessary, based on the new watershed conditions.
- The hydrologic model software version and associated code/computation engine have been revised/updated. Model results commonly change as a result of revisions and updates to software; therefore, existing model calibrations should be checked within revised and updated model versions to ensure that

model calibrations are sufficiently accurate and revised, as appropriate.

It is recognized that model reviews and recalibrations may not be practical for all project watersheds due to monetary limitations and a lack of obvious benefit (e.g., low hazard structures, model calibration accuracies only slightly less than acceptable, etc.) for performing further studies. For these reasons, engineering judgement is recommended for recalibration studies on a case-by-case basis.

Conclusion

While hydrologic model calibrations, validations, and verifications are not always required, it is good practice to conduct these evaluations to develop an understanding of the reliability and confidence of model results.

For project watersheds where observed or measured data are readily available, a calibration process should be seriously considered such that a high degree of confidence and reliability in model results can be developed. At a minimum, pseudo-calibrations should be considered for all project watersheds due to their relative ease of implementation (e.g., USGS regional regression equations). Pseudo-calibrations may only be capable of providing basic "sanity checks" of model results; however, this is certainly preferable to performing no verifications at all and relying purely upon the "black magic" associated with model watershed input parameter selection using empirical and potentially overly conservative methodologies.

In closing, let's think of model calibration, validation, and verification in this light: Would a chef who is trying to impress a food critic by preparing a complicated dish simply follow a recipe and serve the dish without tasting it first? Any good chef would definitely *verify* the taste prior to serving it. The chef may even *validate* the taste at several intervals throughout the cooking process to ensure it is "up to snuff" and make adjustments and *calibrations,* as required. A pinch of initial abstraction, a dash less roughness, and a smidgen more infiltration could be just what you need to take your model from being "ugh, meatloaf again?" to "winner, winner, chicken dinner!"

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CONTINUOUS MONITORING PREFERRED…………

Inspecting Corrugated Metal Pipes in Embankment Dams

Introduction

Until about the 1980s, corrugated metal pipe (CMP) was commonly used for outlet conduits to convey water through earth embankment dams. Typically now used only in low-hazard dams, CMP are not appropriate for use in significant- and high-hazard dams. Many state dam safety regulations now preclude the use of CMP in these higher-hazard structures or they impose rigorous corrosion standards. However, due to hazard creep of low-hazard dams, regulators and dam owners all too often find themselves in a position of having deteriorated CMP's in those critical structures.

CMP also has several serious disadvantages, such as susceptibility to corrosion and abrasion [1]. Due principally to its vulnerability to corrosion, but also because of the potential for other deficiencies (e.g., damage during installation, improper joint connections, etc. described later in this article), the use of CMP as a conduit has been attributed to earth embankment dam failures in the western United States [3].

CMP conduits may be overlooked by dam owners during routine dam inspections because these conduits are often not easily accessible and owners may not be aware of the possibility of failure, or even of their presence. This can lead to a potentially dangerous "out of sight and out of mind" approach. In some cases, CMP conduits were extended during a previous embankment raise with a more durable concrete conduit section, and therefore, only the concrete is visible on the downstream end. Depending on its use, CMP typically has a service life of 25 to 50 years. However, there have been cases when CMP has deteriorated in less than 7 years, given certain soil and water conditions [1]. Most dams, even low hazard dams, have a service life greater than 50 years, meaning that most CMP conduits can be expected to be a potential failure pathway during the service life of every dam where they have been used. It can be reasonably expected that a CMP conduit will need to be repaired or replaced during the life of a dam.

Figure 1. A CMP Conduit Being Installed [1].

This article will explain:

- How to inspect CMP conduits within earth embankment dams;
- How to recognize common deficiencies associated with CMPs; and
- How to determine whether to monitor, repair, or replace the CMP.

CMP Conduit Inspection Techniques

CMP conduits should be inspected by qualified and trained individuals on a frequency representative of the dam's hazard classification. High- and significant-hazard dams are typically inspected on an annual basis, which would include external inspections along any conduits. Internal inspections of conduits for high- and significant-hazard dams are typically recommended on a 4- to 5-year frequency [1]. For low-hazard dams, external inspection may be as infrequent as every 5-6 years and internal conduit inspections every 10 years [1]. Flood control dams that do not retain a pool under normal operating conditions may have less frequent inspections per some state guidelines. The frequency of inspections may need to be increased if accelerated corrosion of the CMP is observed or there is a change in the operating conditions of the reservoir that make problems apparent (e.g., lower pool level exposing previously submerged portions of the CMP). More detailed information regarding inspections can be found in *Technical Manual: Conduits through*

Embankment Dams, produced by the Federal Emergency Management Agency [1]

It is preferred to seal off all water flow and drain the CMP prior to conducting an inspection. In some cases water shutoff is imperative to allow even remote camera access. Many deficiencies within a CMP conduit can be hidden by just a few inches of water. Shutting off the water supply to a conduit may require preplanning as gates or valves that have not been operated in many years may need to be closed or reservoir water levels may need to be lowered to allow water to be stored instead of released during the inspection.

The CMP conduit should be relatively clean and free from obstructions prior to conducting an inspection. Cleaning of the conduit is a preferred preparatory step, as dirt and debris can hide deficiencies within the conduit. Obstructions should be removed prior to conducting an inspection. Several methods may be used to clean the conduit, such as flushing, using a cleaning pig, or pressure washing. The cleaning and inspection crew must exercise caution when using any of these methods as they may accelerate deterioration of a CMP conduit, especially if the conduit is already partially deteriorated or corroded.

CMP conduits are typically inspected using one of two methods: camera inspections or manned entry. Manned entry should only be used when it is safe to do so, including adequate isolation from water sources, sufficient pipe diameter, and implementation of confined space protocols. Both of these methods are discussed in more detail below.

Camera Inspections

Unmanned camera inspections can include the use of manually or power propelled systems equipped with still, real-time and recorded video, and/or closed-circuit television (CCTV) cameras. Utilizing a CCTV camera mounted on a self-propelled robotic crawler (as shown on Figure 2) is the most common way to effectively inspect a CMP conduit. An operator controls the movement of the crawler and the operation of the CCTV camera. Real-time video is transmitted to an aboveground monitor, which the operator uses to determine where to move the crawler and where to focus the camera.

The CCTV camera should be capable of operating in 100 percent humidity and should have a rotating camera head so that all features and defects of the conduit can be inspected thoroughly. The camera should have a self-leveling head to keep the camera upright through the video inspection. Camera lighting should be sufficient to provide a clear, in-focus picture of the entire periphery of the conduit.

Figure 2. CCTV Camera on a Pipe-Crawler Being Inserted into a Conduit (courtesy Drains Kleen).

The camera should also come to the site equipped with a remote-reading footage counter so that features or deficiencies of the conduit can be specifically located. The location and condition of all features and deficiencies must be logged by the operator. This allows comparison and contrast of the current inspection with all past and future inspections. It is desirable for the operator to provide a voice description of observations within the video recording, if possible. The inspector should provide the dam owner with a copy of the video inspection on a DVD disc or a USB flash drive. The dam owner should provide a written summary of the findings and conclusions of the internal inspection, and the full video record, to the state dam safety regulator.

Typically, the most accessible entry point is at the downstream discharge portal of the pipe. If there is flow within the pipe with reservoir drained, the camera should be moved to the upstream end of the conduit and the inspection should continue towards the downstream end so that any flow within the conduit is moving along with the camera rather than splashing against the camera lens. The operator should be instructed to stop the camera and inspect all features (such as joints, gaskets, gates, etc.) and all deficiencies/damage (no matter how seemingly minor they may be). The camera should focus on the feature or deficiency and pan around as necessary to obtain a complete, unobstructed view. When traveling through the conduit, the camera should proceed at a speed that ensures no features or defects are overlooked. Frequent stopping to pan and zoom to highlight areas of interest should be expected, especially in conduits of suspect condition.

It is strongly recommended, but not absolutely necessary to have an engineer present during routine inspection. However, if an engineer is not present, the inspection should be recorded and conducted by an experienced operator. It is recommended that the inspection video be reviewed by an engineer so that they may evaluate the results. We recommend the CCTV operator be Pipeline Assessment Certification Program (PACP) certified, as these operators will have specific training to determine the overall condition of the conduit and the severity of any deficiencies.

Advantages of CCTV camera inspections include:

- No manned entry of confined spaces is required.
- The CCTV camera is able to fit into conduits as small as 6 inches in diameter.
- The CCTV camera provides a recording that is easy to compare to past or future recordings to determine how the condition of the conduit has changed over time.
- The CCTV recording can be shared with the dam owner's engineer for off-site evaluation.

Disadvantages of CCTV camera inspections include:

- It can be difficult to navigate the CCTV camera around gates or valves within the conduit (especially in smaller diameter conduits).
- Inexperienced CCTV camera operators can overlook deficiencies within the CMP conduit.

Some CCTV contractors may promote the use of "push" style CCTV systems. As their name implies, these cameras are pushed into the conduit using a stout cable or rod. Using a push style CCTV camera is less desirable as there is no way for the operator to control the angle of the camera and the dam owner will not be able to see any features or deficiencies clearly. An additional inspection with a camera mounted on a robotic crawler may be required as a follow up to a push style CCTV inspection, which can add time and expense to the inspection process.

Using a mobile video camera, such as a GoPro®, mounted on a sled (as shown in Figure 3) is a cost efficient method to inspect straight (without bends or undulations) conduits, especially conduits at remote dam sites given its small size and ease of transport. The sled can be easily manufactured and attached to a metal push pipe with couplers to extend the sled in 6-foot lengths, as necessary. This style of system will allow the conduit to be inspected by providing video and pictures, but has limitations associated with the lack of panning capabilities and maneuverability of the camera. See our previous Western Dam article You Con-du-it; How to Fix a Leaky Pipe for more information on the mobile-camera sled system used commonly by the Montana and Colorado Dam Safety branches.

Dam owners should expect to pay somewhere between $3 and $6 per linear foot of conduit inspected, plus mobilization costs, for a CCTV camera mounted on a crawler system. The above described manually-propelled sled system can be constructed for about the cost of one or two CCTV crawler inspections.

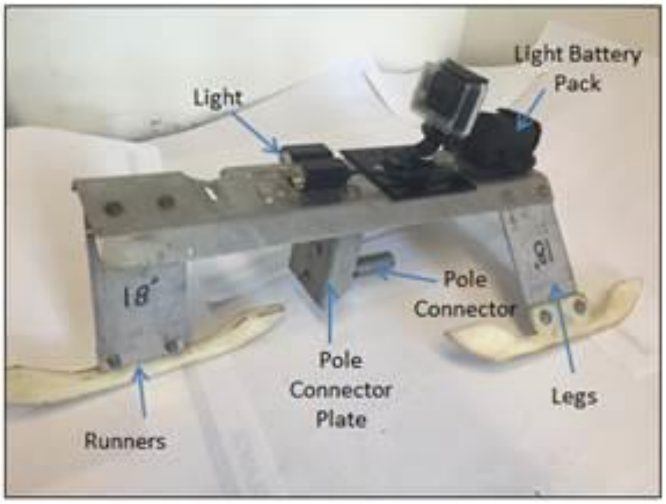

Figure 3. Camera Mounted on Inspection Sled.

Manned Entry

In some instances, it may be possible to inspect CMP conduits via manned entry. The conduit should be at least 36 inches in diameter to safely conduct a manned entry inspection.

Safety is an important consideration with a manned entry inspection. Per OSHA regulations, a confined space is defined as a place with "…limited or restricted means for entry or exit and is not designed for continuous occupancy" [4]. At a minimum, all CMP conduits through dams meet the OSHA definition of a confined space. Furthermore, most CMP conduits through dams will meet the OSHA definition of a permit-required confined space, meaning that special regulations and procedures apply and specialized safety equipment (such as hoisting winches, atmospheric monitors, mechanical ventilators, etc.) will be required to enter the conduit. OSHA regulations for confined spaces must be reviewed and a proper safety planning must be carried out prior to conducting any manned entry inspection.

Advantages of manned entry inspections include:

- Manned entry allows for a set of eyes to focus on the problem, instead of just a camera lens.

Disadvantages of manned entry inspections include:

- Safety precautions must be taken prior to manned entry of CMP conduits. Injury or death could result from an improper effort.
- Only conduits larger than 36 inches in diameter can be inspected via manned entry.

Common Deficiencies in CMP Conduits

Deficiencies within CMP conduits are generally due to either corrosion or construction defects. The presence of either of these types of deficiencies, when not detected and remedied, has the potential to progress to a dam safety incident and even dam failure.

Corrosion Leading to Internal Erosion of Soils

CMP conduits are especially susceptible to corrosion. The metal within the CMP conduits corrodes due to an oxidative process that involves the formation and release of metallic ions. CMP conduits often corrode from the inside out, due to the presence of water and oxygen within the conduit. If water flowing through conduit contains high sediment it can also abrade the CMP, which reduces the life of any protective coatings. However, corrosion can initiate from the exterior of the pipe depending on site specific factors such as soil composition and moisture. Therefore, upon the first signs of corrosion during interior inspections, it should be considered whether the corrosion may have initiated from the exterior, in which case the deterioration may be more progressed than readily visible from the interior inspection.

The process of corrosion can progress either uniformly or in pitting of the surface. Uniform corrosion is where corrosion occurs evenly over a surface, resulting in a lower rate of corrosion. Pitting corrosion is not uniform and is focused only on a small surface area, resulting in a high rate of corrosion, until a perforation (or pit) eventually develops. Pitting can begin on surface imperfections, scratches, or surface deposits. [1]

The pipe invert is particularly susceptible to corrosion since it is exposed to the flow of water for the longest length of time. CMPs that have inverts with sags could trap water and further increase the potential for and rate of corrosion. Other likely susceptible locations include pipe connections and areas of pipe deformation. Once the corrosion process extends through the wall thickness, a hole or void develops within the conduit, which can allow embankment soils to erode into the conduit. If not detected early, this defect can lead to an internal erosion failure and potentially a breach of the embankment. **Figure** shows a 48-inch CMP internal erosion failure in progress as the result of corrosion.

Figure 4. 48-inch CMP Failure Due to Corrosion

Construction Defects

Construction defects can include joint settlements or slippage and conduit deformations. CMP is flexible and is designed to deform. The surrounding soil provides stiffness and load carrying capacity for the conduit. If the surrounding backfill soil is not adequately compacted or if large equipment is used over the pipe during construction without adequate backfill, deformations are likely to occur. Further, if the foundation is subject to large differential settlements (and therefore spreading), joint slippage may occur. Joint settlements (as shown on Figure 5) provide an immediate path for embankment soils to erode into the conduit. Deformations (as shown on Figure 6) can weaken the pipe and/or introduce strain causing the pipes protective coating to weaken leading to accelerated deterioration.

Figure 5. Joint Settlement in a CMP Conduit [2].

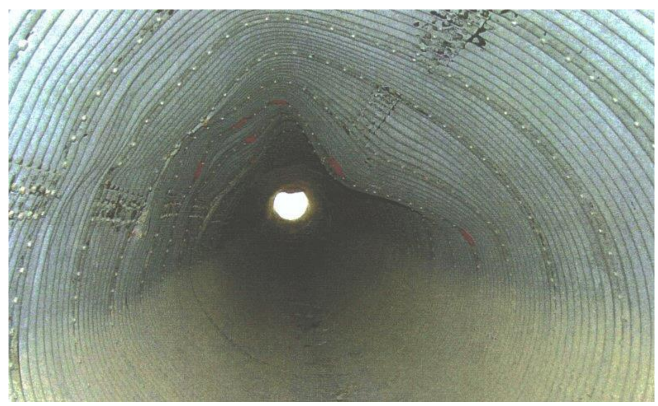

Figure 6. Deformation in a CMP Conduit [1].

Monitor, Repair, or Replace?

The decision to monitor, repair, or replace the CMP conduit can be complex and it involves several factors. This decision is often based on the consequences of potential failure, severity of the defect, the resources available to the owner, and the requirements of the appropriate state dam safety program. Some general guidelines are provided below, but dam owners should make these important decisions in consultation with a qualified engineer.

Continue Monitoring

The dam owner may decide to continue monitoring the following deficiencies without compromising immediate dam safety:

- Minor corrosion, where water is not yet flowing through the walls of the CMP conduit (as shown on Figure 7) – Dam owners should consider inspecting minor corrosion on a more frequent basis to ensure that the deterioration does not worsen to a point where failure is imminent.
- Minor abrasion, where flow through the conduit has removed or damaged the protective coating of the CMP conduit – Similarly, dam owners should consider inspecting minor abrasion defects more frequently to ensure the abrasion does not worsen.

Figure 7: Minor Corrosion in a CMP Conduit [5].

Repair

Moderate deficiencies in the CMP conduit, where a substantial amount of embankment material has not eroded into the conduit or the pipe, has limited deformation can generally be repaired; however, this course of action should be evaluated by an engineer. These include:

- Moderate corrosion, where water is flowing through the walls of the CMP conduit (as shown on Figure 8), but little to no embankment material has eroded into the conduit. Some additional remedial efforts (such as low pressure grouting using traditional cement-based grouts or chemical grouts) should be undertaken if a minor amount of embankment material has eroded into the conduit resulting in suspected void(s) along the outside of the conduit.

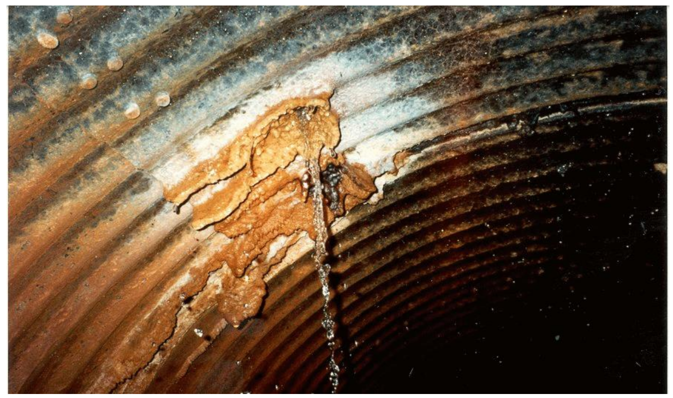

Figure 8. Moderate Corrosion in a CMP Conduit [1].

Replace

It may be necessary to replace the CMP conduit in instances where the conduit is either structurally deficient or a substantial amount of embankment material has eroded into the conduit leading to large voids along the outside of the conduit. Some specific examples include:

- Construction defects, where the CMP conduit has settled or deformed (as shown previously on Figures 5 and 6)
- Major corrosion, where the CMP conduit is no longer structurally sound (as shown on Figure 9)

Repair and Replacement Methods

An in-depth discussion of the repair and replacement methods available for CMP conduits is beyond the scope of this article; however, dam owners should be aware that several effective methods are available. Repair methods include cured-in-place pipe (CIPP), sliplining, spiral-wound liners, and sprayed liners. Some of these methods are discussed in other articles of *Western Dam Engineering Technical Note*, such as:

- Low-Level Conduits – Rehab or Replace (Volume 1, Issue 1, 2013).

- [You Con-Du-It; How to Fix a Leaky Pipe (Volume 2, Issue 2, 2014).]
- [You Down with CIPP? Yeah! You Know Me! (Volume 4, Issue 1, 2016).]

Replacement methods will typically involve an open-cut to ensure that the deficient CMP conduit is removed and a new properly designed and constructed conduit is installed. Replacing the CMP conduit has the potential added benefit of allowing placement of a filter diaphragm or completing improvements that may extend the service life of the dam embankment.

Figure 9. Major Corrosion in a CMP Conduit [2].

Conclusion

CMP conduits can be a major risk concern for dam owners who may not fully understand their design life limitations and how they structurally fail and can lead to dam failure. The pipe generally shows signs of distress before failure. Regular monitoring and inspection of CMP conduits pays off as defects can be detected earlier resulting in less expensive repair options. Eventually; however, if steps are not taken the CMP conduit will corrode enough to allow embankment material to erode into the conduit, and then the only alternative available will be to excavate and replace the pipe. This is a potential emergency situation that may be prevented by early, responsible inspection.

References

[1] Federal Emergency Management Agency (FEMA), *Technical Manual: Conduits through Embankment Dams*, September 2005.

[2] Federal Highway Administration (FHWA), *Culvert Assessment and Decision-Making Procedures Manual*, September 2010.

[3] Great West Engineering, *Manual on Corrugated Metal Pipe in Dams for Montana Dam Owners*, September 2012.

[4] Occupational Safety and Health Administration, 29 CFR Part 1926 (Confined Spaces in Construction – Final Rule), May 2015.

[5] United States Forest Service, Decision Analysis Guide for Corrugated Metal Culvert Rehabilitation and Replacement Using Trenchless Technology, December 2012.