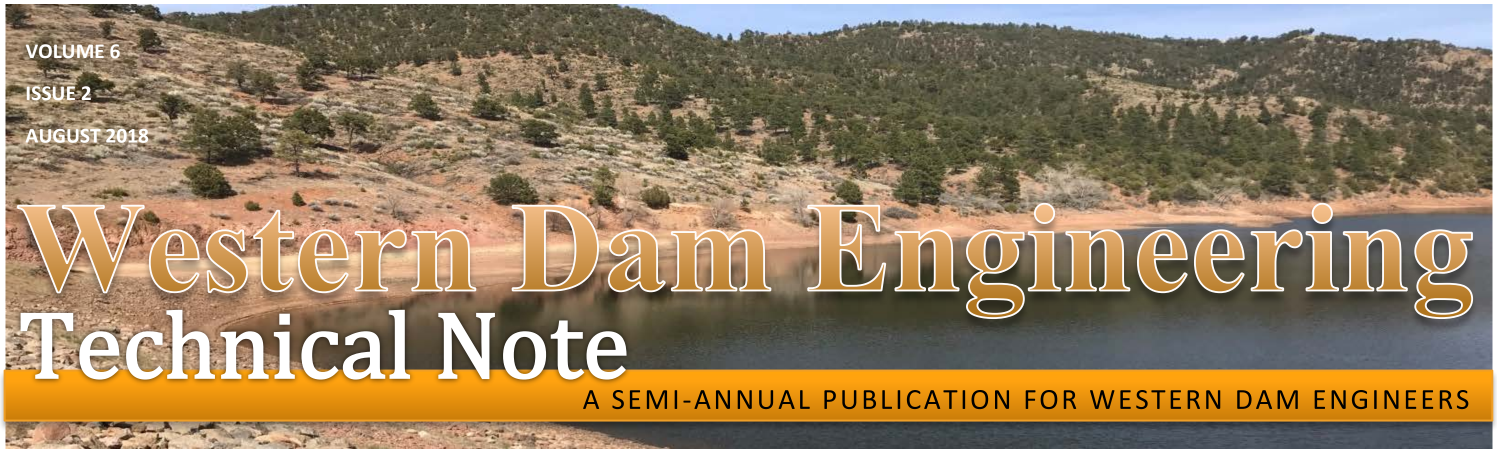

VOLUME 6

ISSUE 2

AUGUST 2018

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 when to use **HEC-HMS versus HEC-RAS**, the impact of **human factors in dam safety incidents**, and important issues when considering **abandoning low-level outlet conduits**. This quarterly 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 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 written, compiled, and edited by AECOM in Denver, CO.

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

Good to Know

Upcoming ASDSO Webinar Dam Safety Training:

- *Drone Technology Integrated into Dam Safety Inspections and Evaluations, October 9, 2018*
- *Why Embankments Crack and How to Fix Them, November 13, 2018*
- *How to Conduct a Successful PFMA - Lessons Learned from Past Successes and Failures, December 11, 2018*

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What the HEC? – Selecting the Best HEC model for the Job

By: Chris Shrimpton, PE, and Chad Vensel, PE

Introduction

You may be familiar with some of the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) software, like the Hydrologic Modeling System (HMS) and River Analysis System (RAS)[1]. These software packages, in particular, are widely used within the water engineering community both domestically and internationally, but what the HEC do they actually do, and when should you use them?

In general, HEC-HMS is used to estimate precipitation runoff rates within a study watershed, whereas HEC-RAS is generally used to simulate the hydraulic interactions between runoff and defined watercourses, floodplains, and hydraulic structures. As such, HEC-HMS and HEC-RAS are often utilized as complementary software packages – that is, surface water engineering studies frequently utilize HEC-HMS to estimate peak runoff rates or runoff hydrographs, which are subsequently input to HEC-RAS to estimate hydraulic characteristics at specific downstream locations.

The primary focus of this article is to present:

- The functionality of HEC-HMS and HEC-RAS;
- Tips and guidance on how to decide when it is appropriate to use each software; and
- Tips and guidance on how to apply each software package to meet study objectives.

Back to Basics

Before discussing the functionality and advantages/ disadvantages of HEC-HMS and HEC-RAS, let's review some of the governing principles and equations on which these software programs are based.

Hydrology vs. Hydraulics

While there are many similarities and overlap between hydrology and hydraulics, there are also distinct differences that are important to understand as they relate to surface water engineering studies.

Hydrology "is concerned with the circulation of water and its constituents through the hydrologic cycle. It deals with precipitation, evaporation, infiltration, groundwater flow, surface runoff, streamflow, and the transport of substances dissolved or suspended in flowing water".[2]

Hydraulics, on the other hand, is "the study of practical laws of fluid flow and resistance in pipes and open channels".[3] More simply, hydraulics focuses on the characteristics of surface runoff and flow, particularly within defined watercourses and hydraulic structures, like bridges, culverts, diversions, etc.

Hydrologic analyses are generally focused on a macro-scale (refer to Figure 1) and are typically the first step in analyzing a water system in order to determine the quantity of water and rate at which it reports to a particular location. Hydrologic flood routing is typically lumped, which means it is calculated as a function of time based on the continuity equation (i.e., conservation of mass) without accounting for spatial variability.

The results of a hydrologic analysis can then be used in a hydraulic analysis to determine how that water interacts with a channel or hydraulic structure to determine specific hydraulic characteristics such as flow depth, velocity, shear stress, etc. Hydraulic flood routing is typically distributed, meaning it is a function of time and space, relying on conservation of momentum as well as mass.

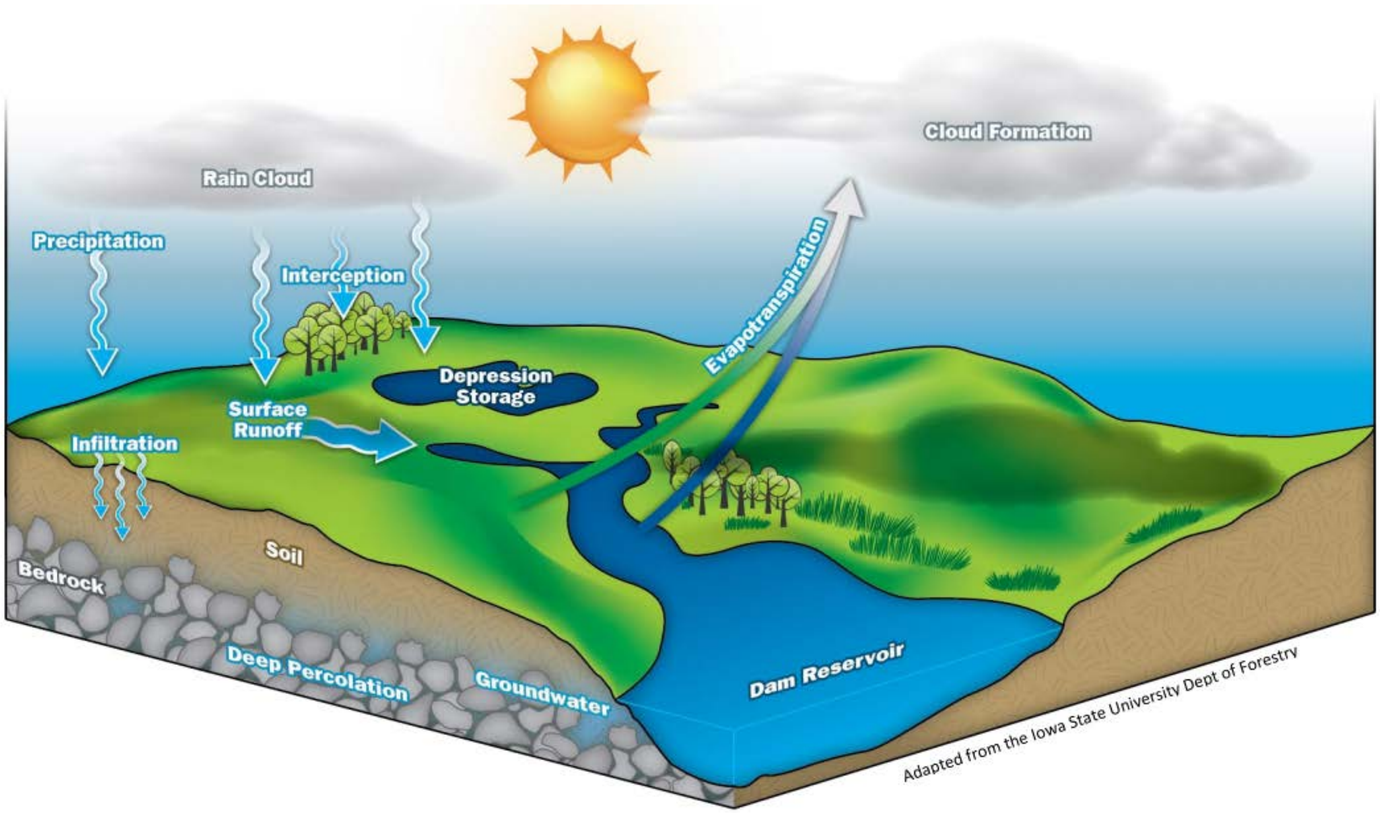

Figure 1. Total rainfall-runoff process with losses

Flow Equations

Energy (Modified Bernoulli) Equation [4]: Applied for steady (i.e., constant and no attenuation) flow applications in HEC-RAS. It is generally more appropriate for gradually varied flow conditions as compared to rapidly varied flow conditions (i.e., rapid transitions between subcritical and supercritical flow).

$$Z_2 + Y_2 + \frac{a_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{a_1 V_1^2}{2g} + h_e$$

Momentum Equation [4]*:*

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial y}{\partial x} - g(S_o - S_f) = 0$$

Kinematic Wave

Diffusion Wave

Dynamic Wave

Kinematic wave: The simplest form of the momentum equation. It assumes that flow is steady, uniform (i.e., constant flow depth and velocity for a given cross section and channel slope) and gravity forces and friction forces balance each other (i.e., friction slope is equal to the channel bed slope). This applies to uniform channels with steep slopes and no backwater effects. This is the only version of the momentum equation available in HEC-HMS. If backwater effects are important, HEC-RAS should be used.

Diffusion wave: This form of the momentum equation incorporates pressure forces in addition to gravity and frictional forces. This is the default equation used in 2D HEC-RAS analyses and is generally suitable for most applications. However, in complex flow situations, the full dynamic wave equation could be more appropriate.

Dynamic wave: This is the most accurate equation available in HEC-RAS (both one- and two-dimensional) and should be used when backwater effects are present and when rapidly varied flow conditions (e.g., highly dynamic floodwaves, abrupt expansions and contractions, mixed flow regimes, hydraulic jumps, etc.) are anticipated.

Hydrologic Modeling using HEC-HMS

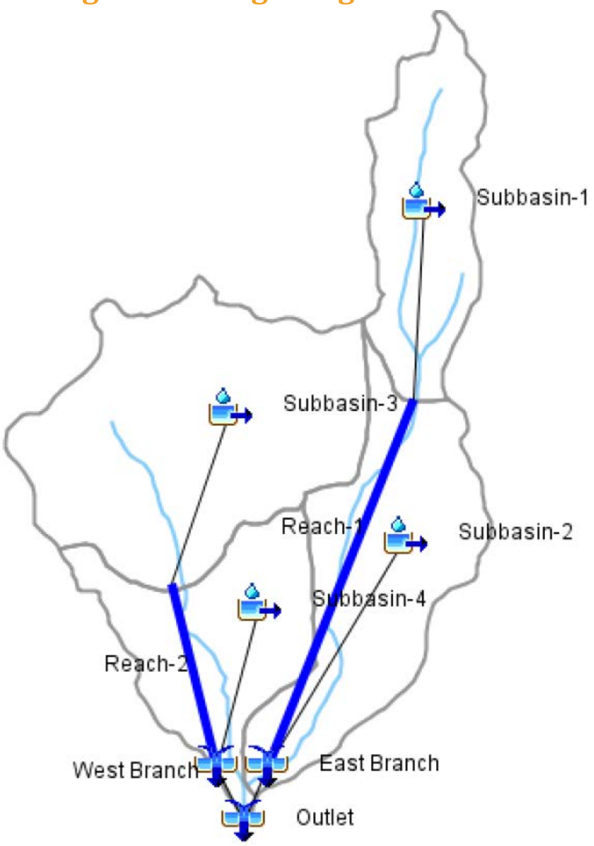

Figure 2. Schematic of typical HEC-HMS watershed model[5]

HEC-HMS is designed to simulate hydrologic processes of watersheds (refer to Figure 2), typically with the intent of estimating runoff hydrographs at various locations within a system. Some other functions that can be performed in HEC-HMS include uncertainty analyses (i.e., Monte Carlo simulations), erosion and sediment transport, and water quality analysis.

Some typical components of a hydrologic model include precipitation, infiltration, runoff transformation (e.g., unit hydrograph), evapotranspiration, snowmelt, and baseflow. The level of effort to develop a HEC-HMS model will vary depending on complexity of watershed and precipitation inputs. Guidelines for selection of some typical input parameters are presented in Western Dam Engineering Technical Note (WDETN) Volume 2, Issue 1 [6]. Some tips for calibrating and validating hydrologic models are presented in WDETN Volume 5, Issue 1 [7].

Desired outputs from HEC-HMS typically include precipitation, surface runoff volumes, water surface elevations, and hydrographs. HEC-HMS is commonly used for reservoir routing evaluations; however, if the reservoir is relatively long and shallow, as is the case with many run-of-the-river and low head dams, a hydraulic model like HEC-RAS could be more appropriate.

Hydrologic channel routing can also be performed to provide coarse estimates of channel flood depths. Hydrologic channel routing methodologies typically utilize simplifying assumptions and empirical data to implicitly simulate flood attenuation and routing. Some of these methodologies include [5]:

- Kinematic Wave;
- Lag;
- Modified Pulse; and
- Muskingum/Muskingum-Cunge.

The most appropriate uses for HEC-HMS include:

- Estimating watershed runoff peak flow rates, volumes, and hydrographs;
- Performing reservoir flood routing for deep, wide reservoirs in which flow velocities are generally negligible;
- Runoff timing and course estimates of channel flow depth within stream networks;
- Screening-level hazard determinations for remote dams without substantial downstream hazards; and
- Hazard determinations for mountain dams with steep downstream channels (as discussed later, steep channels can be problematic in HEC-RAS).

Some applications for which HEC-HMS is not suitable include:

- Explicitly simulating hydraulic structures (in some cases, rating curves or other approximations can be used as a supplement) like bridges and culverts;
- Simulating reservoir and diversion gate operations;

- Simulating backwater effects due to hydraulic structures and channel constrictions;
- Explicitly simulating channel/floodplain storage (i.e., flood attenuation); and
- Simulating rapid transitions between subcritical and supercritical flows.

Hydraulic Modeling using HEC-RAS

HEC-RAS is designed to perform one-dimensional (1D) and two-dimensional (2D) hydraulic evaluations for natural and constructed channels, overbank/floodplain areas, levee-protected areas, reservoirs, etc. Some typical components of a hydraulic model include topographic data (i.e., cross-section or mesh), surface roughness (i.e., Manning's "n" roughness coefficients), and inflow discharge (i.e., constant flow or hydrograph). HEC-RAS cannot simulate precipitation, watershed response, infiltration, or snowmelt; however, some of its capabilities include:

- Simulating hydraulic characteristics within a channel/floodplain (e.g., water surface profiles, etc.);
- Simulating hydraulic characteristics at structures such as bridges and culverts; and
- Developing flood extent and temporal based hydraulic characteristics for inundation mapping.

HEC-RAS modeling is typically performed for either steady (i.e., constant flow) or unsteady (i.e., flow changes with time) simulations utilizing 1D (i.e., flow travels only in the downstream direction) or 2D (i.e., flow travels both longitudinally and laterally downstream) geometric domains. The following sections describe these modeling options and provide insight on the advantages and disadvantages of each. The RAS Solution [8] is also a great source for RAS-related tips and tricks. Reference [9] is a good resource for determining if your model results are reasonable.

Steady vs. Unsteady Flow

Steady flow analyses assume a constant discharge through the entire reach and use the energy equation, which does not account for changes in momentum. Unsteady flow analyses using the St. Venant equations (i.e., conservation of mass and momentum) are capable of modeling changing discharge over time (i.e., hydrographs).

Some advantages of steady flow analyses include:

- Greater stability;
- Shorter run times;
- Generally less time intensive overall; and
- Peak discharges are input rather than entire hydrographs, making it easy to model many scenarios in a short period of time.

Some disadvantages of steady flow analyses include:

- Reduced accuracy due to simplifying assumptions of the energy equation;
- Inability to account for channel and floodplain storage effects; and
- Inability to provide temporally based hydraulic characteristics, like floodwave arrival times, detention durations, overtopping durations, flood volumes, etc.

Some advantages of unsteady flow analyses include:

- Greater accuracy given that the more sophisticated St. Venant equations are used and account for channel/floodplain storage effects on flood attenuation;
- Temporally based results can be easily obtained; and
- Reservoir routing and dam breach analyses can be simulated.

Some disadvantages of unsteady flow analyses include:

- Increased computational intensity, longer run times, and increased instability;
- Models can be especially unstable for some geometric and hydraulic conditions like steep or highly irregular reaches, low flood depths, and flashy hydrographs, particularly with 1D models; and
- Models can be significantly more time intensive overall due to instability troubleshooting.

In general, unsteady analyses are more accurate and appropriate if a higher degree of accuracy is required and time/schedules allow. Steady flow analyses could be more appropriate for very long or steep reaches as well as stream networks with multiple watercourses and junctions. Steady flow analyses may also be appropriate for rating curve evaluations or simple models where only peak discharges are evaluated and accuracy is less critical.

1D vs 2D

1D and 2D model geometries are developed based on topographic data like DEMs and TINs (sourced from various federal, state and local agencies) as well as site-specific surveys. 1D models feature a select number of cross-sections at specific locations within a study reach (refer to Figure 3), whereas, 2D models feature a mesh that covers the entire study reach (refer to Figure 4).

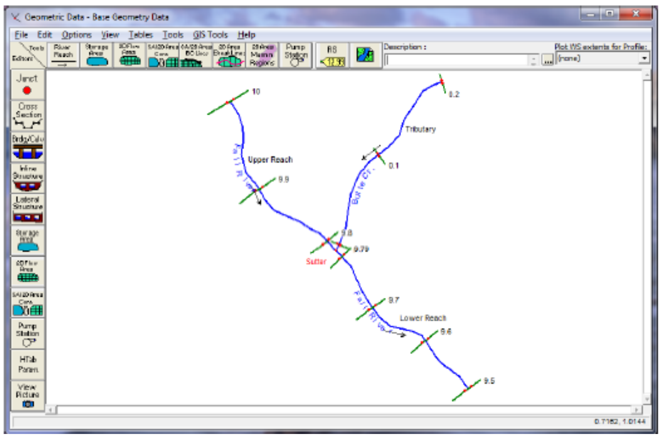

Figure 3. Example of 1D HEC-RAS model geometry [4]

A 1D model may be best suited when the following are true:

- Flow is generally one-directional (i.e., downstream) and does not spread dramatically into the floodplain;
- The reach is relatively uniform with limited expansion or contraction;
- The floodplain is narrow relative to the main channel. The width of the floodplain should be less than three times the width of the main channel;
- The channel is well defined and bounded by steep slopes and channel flow is well connected to overbank flow. Channels that are raised above the floodplain may not be well suited for a 1D model; and
- The desired outputs are simple profile characteristics along the main channel such as energy grade line, average channel flow depth, and velocity, channel shear stress, etc.
- Other benefits of a 1D analysis include:
- Flow characteristics at individual cross-sections are more readily available than they are with a 2D analysis;
- Run times are typically much shorter with a 1D analysis, especially for very large models;
- Pressure flow at bridges can be modeled in a 1D analysis, which is a feature that is not yet available in 2D;
- Industry familiarity with 1D, which has been used for decades as opposed to 2D, which is a relatively new feature; and
- Model result verification and detailed checking can be completed much more easily for 1D scenarios as compared to 2D scenarios.

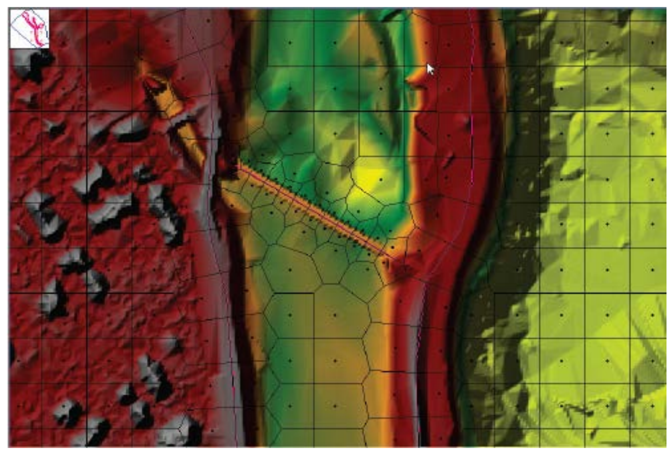

Figure 4. Schematic of typical 2D HEC-RAS computational mesh. [4]

Conversely, a 2D model may be best suited when the following are true:

- Flow is multi-directional and is expected to spread dramatically. This includes reaches with abrupt expansions/contractions, urban areas with buildings and other flow obstructions, and narrow bridge crossings;
- The floodplain is wide compared to the main channel. A 2D model may be most appropriate if the width of the main channel is greater than three times the width of the main channel;
- The terrain is very flat such as wetlands, estuaries, deltas, etc.; and
- The study is focused on a stream network with multiple watercourses and junctions or lateral structures.

Other benefits of a 2D analysis include [4]:

- 2D models directly incorporate topographic and land cover data and do not required third party GIS software for mapping;
- The ability to produce detailed animations of flood wave progression in 2D space, including depth, velocity, shear stress etc.;
- Flood characteristics can be obtained at locations other than cross-sections more easily than in a 1D model;
- 2D models eliminate the need for subjective components such as ineffective flow areas, levee markers, and cross-section orientation;
- Inundation mapping is much easier than 1D; and
- Unsteady flow analyses are often more stable with a 2D model than a 1D model.

There is often a misconception that a 2D analysis is much more time-consuming and expensive than a 1D analysis. This is not always the case, as a highly complex system can be much easier to analyze with a 2D model, while simpler systems may be better suited for a 1D model. Often it can be prudent to combine these models, using 2D where detailed results are required and 1D elsewhere.

Ultimately, there is not necessarily a right or wrong answer when deciding between a 1D and 2D analysis. Often, the 1D or 2D decision is based on the personal preference of the modeler as well as the study objectives and requirements.

Dam Breach Analyses

Both HEC-HMS and HEC-RAS are capable of modeling dam breaches. As discussed above, HEC-HMS is intended to model hydrologic systems, while HEC-RAS is better suited for hydraulic analyses. However, the choice of which software to use when modeling a dam breach will vary depending on the application.

Some advantages of using HEC-HMS are that it is a simple setup, data requirements are minimal, and it is numerically stable. However, hydrologic streamflow routing does not account for backwater, and the results cannot be easily used to develop inundation maps.

Figure 5. Image of Teton Dam failure [10]

HEC-RAS uses full dynamic routing to perform breach analyses, which accounts for backwater effects. Also, outputs can be easily and quickly used to develop inundation maps directly in the software. However, the data input for dam breaches in HEC-RAS is more complex than HEC-HMS and simulations can become numerically unstable, especially in steep reaches.

HEC-HMS is commonly used to develop a breach hydrograph unless tailwater is expected to significantly influence breach outflow. The hydrograph from HEC-HMS can then be used as an input to an unsteady HEC-RAS model. However, if backwater is anticipated to be significant, such as with low head dams, mild slopes, or abruptly converging downstream reaches, HEC-RAS is likely to be more appropriate.

The piping dam breach event at Teton Dam occurred at location on the embankment well above the valley floor (refer to Figure 5). Breach outflows were not constrained by the downstream valley geometry. As such, it would likely be appropriate to use either HEC-HMS or HEC-RAS to model this breach event as backwater impacts were likely negligible.

Backwater

Bridges, dams, and other stream obstructions can create backwater, which influences flow conditions upstream of the obstruction. Before immediately embarking on a HEC-RAS model to evaluate backwater, review the area proximate to the obstruction to determine if the results of a HEC-RAS model could be potentially beneficial. For example, if the backwater does not cause any flooding hazards, it could acceptable to ignore, or assume the obstruction is washed out during an extreme flood or dam breach event. If the study area is steep and flow is expected to be mostly supercritical, backwater effects are unlikely. If there is uncertainty about backwater impacts, one simple technique employed in the past is to perform hydrologic flood routing (using HEC-HMS) to the obstruction and use the peak flow at that location as an input to a steady flow HEC-RAS model of the obstruction.

What are your Objectives?

The objectives of a study will dictate which software (i.e., HEC-HMS vs HEC-RAS) and type of analysis (e.g., steady vs. unsteady, 1D vs 2D, kinematic wave vs. diffusion wave vs. dynamic wave) is most appropriate. Some study objectives to consider when pondering the choice between software and analysis type include required study accuracy (e.g., client/regulatory requirements), schedule, and budget.

Do you want to evaluate detailed flood impacts resulting from a 1 in 100 annual exceedance probability (AEP) flood event within a relatively flat urban area? If so, you'll likely want to develop a 2D unsteady HEC-RAS model using the full dynamic wave equation, which will provide the most accurate estimate of the flood extent and hydraulic characteristics within the study area.

However, if you want an approximate estimate of the flood velocities and depths in an urban area where hydraulic structures and backwater effects are present and flood flows are generally contained within a channel, an unsteady, 1D HEC-RAS model could be appropriate.

Are you responding to a time-sensitive event where somewhat conservative estimates of channel flood depths are required to evaluate downstream levee overtopping potential? If so, HEC-HMS could be appropriate as a first pass at assessing overtopping potential. A steady flow, 1D HEC-RAS model could also be appropriate depending on channel slopes and downstream hydraulic characteristics.

Do you want to estimate the runoff volume into a reservoir resulting from a 1 in 100 AEP precipitation event? If so, you'll likely want to develop a watershed model in HEC-HMS. However, if you want to understand the potential downstream flood impacts resulting from spillway overflows, you might initially want to consider a simple 1D HEC-RAS model using a steady flow analysis.

Q & A

Can I make conservative assumptions and use a simpler model, like HEC-HMS or 1D, steady HEC-RAS?

Channel routing functionality in HEC-HMS does not explicitly account for flood attenuation, channel storage, or backwater effects and should not be used on flat slopes or areas with significant floodplain storage unless coarse estimates of flow depth are all that is required. However, this coarse level of analysis is often acceptable, particularly for screening-level hazard determinations in remote areas or similar applications.

HEC-HMS can be a good initial screening tool. Since the model is easy to set up and not as data intensive as HEC-RAS, running a coarse conservative HEC-HMS dam breach model can provide direction for further analysis. Often, it is not necessary to go the extra mile with a hydraulic analysis - hydrologic modeling could be sufficient.

HEC-RAS should not be used to estimate the hydraulic characteristics associated with steep slopes (i.e., greater than 10 percent) like those associated with drop structures, spillways, steep mountain streams, etc. HEC-RAS results associated with rapidly varied flow conditions (i.e., hydraulic jumps, etc.) may also be questionable. More sophisticated modeling, like computational fluid dynamics (CFD) or a physical model could be required for these types of conditions.

In the interest of time and economy, simplified and conservative assumptions can be applied to many water engineering applications; however, such assumptions must be justifiable to ensure that results are conservative, yet reasonable. Furthermore, the reader is cautioned to forecast the time required to develop such assumptions, as this time plus the time required to develop a simpler model could be greater than the amount of time required to develop a more complex and robust model. Therefore, a more complex and robust model could be a better option.

When do I need to model bridges/culverts?

Bridges and culverts often produce backwater effects that impact flow immediately upstream, although it is not always necessary to model them explicitly.

If the capacity of a culvert or bridge is significantly less than the simulated discharge (e.g., the probable maximum flood is being simulated and the culvert is designed for a 1 in 50 AEP flood event), it may not be prudent to model flow through the culvert and instead assume that the culvert is blocked or washed out (depending upon potential impacts to upstream areas/structures).

However, it would be prudent to include a bridge if mapping a 1 in 100 AEP flood event in an urban area with structures located immediately upstream.

When do I need to model dams in series?

Occasionally, when performing a dam breach analysis, it is necessary to model cascading failures of downstream dams. This applies when the storage capacity of the downstream dam is large relative to the breach outflow of the dam being analyzed. However, it is often safe to assume that smaller dams will be washed out by the breach outflow and can be ignored.

Conclusion

The choice between using HEC-HMS or HEC-RAS comes down to the objectives of the study. HEC-HMS is generally intended for hydrologic modeling (i.e., converting precipitation into discharge, reservoir routing, routing flow through watershed networks, basic channel routing, etc.). HEC-RAS is generally intended for hydraulic modeling (i.e., routing discharge through channels, floodplains, hydraulic structures, etc.). For applications in which either software program could be used, the choice often depends on the degree to which backwater effects are anticipated. For simple, uniform reaches with negligible backwater effects, HEC-HMS is typically appropriate. For flat watercourses where convergence, divergence, or backwater effects are present, HEC-RAS is likely to be more appropriate.

Within HEC-RAS, the choice between steady/unsteady and 1D/2D generally depends on the complexity of the study area, the desired level of accuracy, and time/budget constraints. For reaches where flow does not spread, a steady 1D model could be appropriate. In a flat urban area with bridges and culverts, a 2D unsteady dynamic wave model could be required.

For the evaluation of multiple events, it could be prudent to develop both a simple 1D model and a detailed 2D model and compare the results for a single simulation to understand the sensitivity of the modeling approach. The remaining simulations can be modeled with the approach that is most appropriate given the constraints of the study.

In short, there is not necessarily a right answer as it pertains to modeling hydrologic and hydraulic systems, but it is best to use the simplest/easiest model that meets the needs of the study. Just remember, simple doesn't necessarily mean easy.

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Dam Failures due to Human Factors Do Happen!

Ka Loko Dam failed in 2006 due primarily to owner filling in spillway. Resulted in 7 fatalities, $25M settlement, manslaughter charge and reckless endangerment conviction of owner, 7-month prison sentence, and reported $46M in defense expenditures.

Failure of Big Bay Dam in 2004 resulted in destroying 48 homes, washing out a bridge, and damaging 53 homes, 2 churches, three businesses and a fire station due primarily to inadequate seepage controls and recognizing warning signs.

Oroville Dam spillway incident occurred in 2017 primarily due to inadequate design for foundation conditions of the primary and emergency spillways. Incident resulted in evacuation of 188,000 people and yet to be quantified environmental and economic impacts.

Factoring for Human Factors in Dam Safety Incidents and Failures

By: Jennifer Williams, PE and Jason Boomer, PE

Introduction

Dam safety incidents and failures have been used by engineers, owners, and regulators as a valuable source of information to promote learning and advancement in design, construction, surveillance and monitoring, and emergency management. This will certainly be the case with regards to one of the more recent events that occurred at Oroville Dam in February of 2017. The release of the Independent Forensic Team Report for the Oroville Dam Spillway Incident (Forensic Report) has highlighted, among other lessons, the need to understand the importance of human factors and the role they play in preventing dam safety incidents and failures. As described in the Forensic Report, the field of human factors spans multiple scales including individuals, groups, organizations, industries, and broader social, economic, and political context [1]. The field of human factors is interdisciplinary and draws from fields such as psychology, sociology, economics, and political science, just to name a few [1]. In simpler terms related specifically to dam safety, human factors are the judgments, decisions, actions or inactions of a person or group of people that influence the performance and life cycle of a dam. Human factors, in a sense, represent everything outside the realm of physical science and technical aspects of engineering.

What are Human Factors?

Irfan Alvi[1] was part of the six-person forensic team for the Oroville Dam spillway incident serving as the Human Factors specialist and has conducted multiple presentations and webinars on the topic for ASDSO (see *ASDSO Training link*: Human Factors in the Oroville Dam Spillway Incident). A large portion of the content of this article is taken from Alvi's work, particularly the Forensic Report, and organized into the life cycle components of a dam.

Alvi identifies three categories of human factors that are the primary drivers leading to the potential for failure.

1. Pressure from Non-Safety Goals (e.g., delivering water and power, reducing costs, meeting tight schedules, and political pressures)

[1] President & Chief Engineer, Alvi Associates, Inc.

2. Human Fallibility and Limitations
3. Cognitive Effects of Having to Deal with Complexity

Conversely, human factors which contribute to safety include (a) organizational 'safety culture', with a corresponding humble and vigilant attitude with regard to preventing failure, and (b) numerous best practices related to general design features of dams, and organizational and professional practices. Failures generally result when the human factors contributing to safety are not sufficient to outweigh those contributing to failure.

Human errors can be categorized as "slips" (actions committed inadvertently), "lapses" (inadvertent inactions), and "mistakes" (intended actions with unintended outcomes due to errors in thinking) [1]. With regards to dam safety, mistakes have typically been labeled as the most common type of human error [1]. This article will attempt to highlight some of the more common human factors that have contributed or will contribute to past and future incidents and failures related to the life cycle of a dam. These are discussed in context of the dam design, construction, monitoring and maintenance, and emergency response.

Design

"All men make mistakes, but only wise men learn from their mistakes" – Winston Churchill

The state of the practice in dam safety has evolved significantly over time through knowledge gained from studying dam safety incidents and failures. As we have gained more knowledge about how dams behave under various loading conditions, and how to predict those loading conditions, the industry has responded with changes to typical design criteria and standard design details. For example, filter design for earthen embankments is now common practice and rigid seepage collars have been replaced with engineered filter collars, rendering homogenous dams a practice of the past and a cause for increased scrutiny of existing homogenous dams. Hydraulic fill dams have also proven to be particularly susceptible to poor performance under certain loads and are no longer used in modern practice. Concrete spillways have seen changes in joint details, reinforcement and anchoring design, and the addition of more robust underdrain systems. Other changes have resulted from the advancement of technology in fields like hydrology and seismicity to predict design loads. All of these changes can be attributed to the advancement of technical understanding in the industry.

This evolution of design practices in dam engineering can also lead to practitioners becoming outdated in their knowledge of current standard of practice, requiring diligence and dedication to stay on top of continuing education. It is also difficult for many individuals to recognize their own technical knowledge limitations, and to avoid practicing engineering outside their areas of experience and technical understanding. The acknowledgement that "*I know enough to be dangerous*" should be sufficient warning to stop someone from providing engineering advice beyond their area of expertise. The breadth of technical disciplines in the field of dam engineering is vast, and the depth of understanding one must have to apply engineering methods, criteria and parameters correctly, requires engineers to specialize in specific fields of practice. With all the guidance documents and analytical methods available, engineers must still apply judgement in most all that they do and poor judgement is a human fallibility. This challenge requires a multi-disciplinary approach to most engineering studies, analyses, and design.

HUMAN FACTORS IN DESIGN
❖ Resource, budget and schedule constraints
❖ Insufficient data or technical expertise to understand the data
❖ Insufficient technical expertise of designers and lack of use of design best practices
❖ Lack of multi-disciplinary diversity on the design team
❖ Insufficient design conservatism

Construction

"The greatest mistake is to imagine that we never err." – Thomas Carlyle

The construction phase is similar to design in that it has seen significant changes in generally-accepted best practices and available tools. However, regardless of improvements to equipment, materials, and technology, human factors during construction play a role in contributing to potential failures. There are several common threads between human factors during design and those that occur during construction including the substantial budget and schedule pressures of most projects. The influence of technical understanding, or lack thereof, is just as influential during construction as it is during design. Technical experience is required to be able to modify the design to accommodate unexpected site conditions, verify the design is being constructed as intended, and be able to adequately document the as-built conditions for future reference and understanding. Construction also brings a complex relationship into play with what are sometimes competing interests between the owner, the contractor, and the engineer.

The construction phase considered here includes repairs and other remedial measures constructed throughout the life of the dam. If the repairs are being executed to correct deterioration or changes to the physical condition of the various features, then it is important to understanding the reason *why* those repairs were needed. Understanding the root causes of “symptoms” such as cracked concrete, irregularities in an embankment, seepage, etc. will help in selecting the remediation that not only corrects the symptoms, but prevents the problem from recurring or worsening.

HUMAN FACTORS IN CONSTRUCTION

- Budget and schedule constraints
- Insufficient data or technical expertise to understand the data
- Insufficient technical expertise of contractors and designers
- Competing interests of owner (cost, operations, & schedule), contractor (cost, schedule), and engineer (technical liability, conformance)

Operational Life Cycle

Human interaction that affects the performance of the structure occurs in many forms throughout the operational life of the dam. How the dam is operated, maintained and monitored all influence the performance risks of aging infrastructure.

Operations

Dam operations are influenced by owner financial goals and pressures balanced with their risk management style and regulatory requirements. Operations refer to not only how the facility is operated, but also to the owner’s internal dam safety culture. Owners with different internal cultures will perceive, prioritize, and manage operating risks differently. An owner will prioritize spending based on their understanding of the value gained in terms of managing financial risks.

Investing in formal and periodic dam safety training for operators, engineers, and managers can influence the group’s ability to recognize and respond to developing issues. Training will look different for each of these different groups. Training for operators may focus on how dams fail, site specific PFMs, inspection and monitoring techniques, causes of human error in operations, internal technical resources, and communication protocols. Training for managers and decision makers may focus on dam failure statistics, potential consequences, methods of risk prioritization and risk management. Keeping decision makers within the owner’s organization informed on the importance of dam safety and cost impacts of incidents and failures will help make the case for requests of proactive expenditures.

HUMAN FACTORS IN OPERATION

- Budget constraints
- Insufficient technical understanding and training
- Lack of a strong safety culture of owner/operator
- Lack of an established risk management processes
- Inadequate number of operations staff for the requirements of the project
- Human operational error
- Inability to recognize and respond to developing conditions and warning signs

Monitoring

Visual surveillance and instrumentation monitoring are used in conjunction with each other to identify warning signs that might indicate the onset of a developing failure or incident. When used appropriately they can be very effective at identifying issues in sufficient time for successful intervention and mitigation. However, lack of knowledge, complacency, or overconfidence by inspectors and personnel evaluating monitoring data can lead to warning signs being missed or misunderstood. It is also a common human factor to normalize deviations observed in the physical condition of the structure over time. A crack in a spillway slab that has always been there can be viewed as "normal." In this case more frequent or even more detailed inspections will not identify the crack as a potential issue because it has been labeled as a "normal deviance." In addition, more frequent physical inspections are not always sufficient to identify risks and manage safety, and instead more *comprehensive* inspections and reviews are required when warranted by risks.

The more substantial reviews that occur at a lesser frequency, such as five-year reviews versus annual inspections, often focus on changes based on observations from inspection, surveillance, monitoring, and operations during the prior five-year interval. Instead, these should be periodically supplemented by comprehensive review on the long term performance, including verifying design assumptions and comparing the original design and construction with current best practices. More comprehensive reviews should not only evaluate the physical condition of the dam, but also review the design, construction, operation, and history of past performance of each feature. Each comprehensive review should be conducted with a fresh set of eyes.

Access constraints often prevent regular inspection of certain components such as steep slopes of spillways, embankments, and concrete dams; conduits; towers; etc. Although the advent of drones, ROV and other remote-access camera inspection has lessened this concern, there is still cost and effort involved in conducting these inspections, and technical expertise required to understand the observations.

As with all other phases of the dam's life cycle, technical understanding plays a big role in an effective surveillance and monitoring program. The dam safety surveillance and monitoring program needs to be developed, executed and reviewed by someone who understands and can recognize the relevance of warning signs. A well-informed plan should be developed based on an understanding of how the various components of a dam might fail and what surface expressions may correlate to a developing problem. This is often accomplished in the form of a Potential Failure Mode Analysis (PFMA) which identifies credible PFMs for the various features and the potential warning signs that may be detected in a monitoring program. Traditionally, PFMAs have focused only on breach-type failures resulting in catastrophic release of the reservoir. However, dam safety incidents that don't progress to failure may still result in significant consequences (economic, social, environmental, etc.), particularly for the owner. The PFMs identified during the PFMA process can be utilized as a road map of what to look for during regular and comprehensive reviews. In addition, PFMAs can be a valuable tool in the owner's overall risk management process.

HUMAN FACTORS IN MONITORING

- Budget constraints
- Complacency and overconfidence
- Insufficient technical understanding of owners and inspectors to recognize warning signs
- Normalization of deviance
- Access limitations
- Lack of comprehensive reviews

Maintenance

Aging infrastructure requires periodic maintenance and repairs to continue to perform as designed. It is important to identify maintenance items in a timely fashion and even more important to make sure the repair doesn't cause additional harm. There have been cases were repairs have actually masked the underlying issue, which makes it difficult for future inspections to identify the initial cause before it recurs or progresses undetected.

HUMAN FACTORS IN MAINTENANCE
❖ Budget constraints
❖ Complacency and overconfidence
❖ Insufficient technical expertise
❖ Categorization of significant repairs as "routine maintenance"
❖ Access limitations

Emergency Response/Management

Human factors also play a large role in how an emergency situation is managed from the initial notification to completion of the final repair. It is human nature to either "fight or flight." As an owner, owner's engineer, or regulatory agency it is a notification that we hope never comes, but, when it does how will human factors influence the outcome?

Stress Management

Individuals placed in emergency response situations are impacted by psychological stressors that can impact their mental and physical health. These stressors can ultimately have an effect on one's ability to make critical judgments and decisions during a crisis. The first line in combating stress is preparation. Training, planning, and reviewing available information will better prepare you for an emergency. Preparation is the best "cure" for anticipatory stress [2]. Most important is to remain calm, take a deep breath, and don't be afraid to ask for help.

Communication Styles

During an emergency situation the effective sharing and transmittal of information is critical. Emergency Action Plans (EAPs) are available for most, if not all, significant to high hazard dams and contain scripted procedures for making notifications. However, what the EAP doesn't contain is a guide for the different types of communicating styles that will be necessary to use during an emergency situation. Communicating to different groups of people requires different styles and techniques to convey the appropriate information in an appropriate manner. Therefore, different individuals may be assigned to communicate to the different groups. The various groups of people that will be in the communication loop include:

- Media
- Public
- Emergency managers
- On-site owner representative(s)
- Owner decision makers
- Regulatory agencies
- Contractors

Initial conversations with the media or public may not be best handled by the owner or engineer, as they are under the duress of figuring out the problem and deciding on a path forward. However, almost any emergency management team has a designated Public Information Officer (PIO) available. PIO's can be city, county or state personnel who have been trained to take technical verbiage from experts and convey it to the public in a manner that can be understood. Owners and engineers do not have an obligation to speak to the public or media. They do, however, have an obligation to get the appropriate information out to the public. With a simple request for assistance from the local emergency management team, the closest or designated PIO could assist. Information provided to the public should be concise, accurate, and delivered in layman terms to limit the potential for misquotes or fake news.

Emergency managers may not comprehend the technical issues that are influencing the decision making process, and therefore need information conveyed in a manner which describes the likelihood of various scenarios and the associated implications to the public. Therefore, information provided to emergency managers should be non-technical in nature, but provide a clear picture of the developing situation and potential consequences. FEMA maintains a listing of state emergency management agencies: Emergency Management Agencies. The local city or county may also have emergency management representatives and resources.

When briefing owners and regulatory agency representatives, the information should be provided in a technical manner to present a clear understanding of the incident.

ASDSO and other organizations offer training in effective communication techniques specific to emergency situations.

Judgment, Decision Making and Selecting a Response

When it comes to judgment and decision making during a crisis there can be a lot of opinions on how to address the situation. It's important to consider all the alternatives, but it's even more important to identify one decision maker. The opinion of a dam owner may be different than that of an emergency manager, which both may be different from the opinion of a regulatory agency. It's the decision maker's responsibility to balance the opinions and expertise in order to make the best decision. The decision maker may need to make quick decisions even when there may be little, no, or ambiguous information. This can place a significant mental stress on the decision maker and even the supporting personnel.

Selecting an appropriate response requires developing an understanding of the cause, the various response alternatives and their effectiveness, and their potential implications. This is where pre-planning for emergency response can reduce human-caused mistakes. Reaching out to the appropriate network of individuals with qualified technical experience to help guide the decision makers on the potential alternatives and their effectiveness, as well as the operations staff to provide insight on the feasibility, execution, and implications of the various alternatives is required to make an informed decision.

Incident Management

Just as there should be a clear line of authority for decision making, there should be an individual assigned to manage the incident on-site. First and foremost, stay calm. Seek advice from trusted experts and make a decision. Maintain some level of flexibility to recognize when a decision is not working and allow a change in course. Use the steps outlined in the EAP as a guide. This is not the time to try and be a hero, understand your limitations. Interact with the incident command center, if established by the emergency management team, and ensure communication protocols are understood. Physical boundaries to the site are important for the safety of the public and also emergency responders. Don't forget the number one priority is public safety and the safety of the emergency responders.

Documentation

Document, document, document. This may be one of the last things on your mind but it is very important to document decisions and actions during the incident. Take notes, photographs, draw sketches, and possibly take videos. Once the incident has been resolved the post-emergency documentation begins. A written report, letter, or memorandum should be prepared while the judgments, decisions and actions taken during the incident are still fresh. Provide an accurate account from beginning to the end. The documentation taken during the incident will prove invaluable. Include a detailed section of lessons learned. The better the documentation the better others who may be faced with a similar situation will be prepared.

Summary

The behavior of dams and other physical systems are subject to the laws of deterministic physical science. Because of human's interaction with the physical features which they design, construct and operate, there are numerous factors outside the realm of physical science and technical aspects of engineering that affect the behavior of the physical system. Simple mistakes, misoperation, negligence, or oversights can increase the possibility of failure. These slips, lapses and mistakes can and do occur at various phases throughout the life of the dam. Ironically, this type of human inevitability to be fallible can best be counteracted with other human behaviors related to design, construction, organizational, and professional best practices. Human effort is needed to create and maintain order and achieve safety. But human effort sometimes falls short. When the human factors contributing to failure outweigh those contributing to safety, failures can (and likely will) result.

> *In engineering, we always have interacting physical and human factors.*
>
> *Human factors contribute both to Failure and to Safety.*

Contributions to Failure	Contributions to Safety
• Pressure from non-safety goals • Human fallibility and limitations • Complexity • Human errors • Inadequate risk management	• Safety culture and training • Best practices - General design and construction features - Organizational & professional practices

Key Takeaways

FAILURES HAPPEN and human factors are a major contributor. Failures can result in catastrophic consequences as presented in the three cases at the beginning of this article. Individuals and organizations that understand these consequences are better positioned to recognize the contributors to failure and the contributors to safety. Once these contributors are identified and understood the benefits associated with safety investments becomes clear.

Managing human factors that affect failure is achievable! Becoming aware of the human factors in a conscious framework is Step 1.The table below summarizes key human factor best practices to achieve safety.

Achieving an A+ rating on all of the best practices is a lot of effort and is difficult to achieve. Technical knowledge is probably the most important factor toward achieving safety. People who are not experts in a given field need to recognize their limitations and seek input from other specialized expertise. Too often the individuals who have the least amount of expertise are often the ones with overconfidence, a conundrum specifically known as the Dunning-Kruger effect.

Human factor best practices are a complex and vast field than can be overwhelming to comprehend as a whole. However, it is important to understand their role in preventing dam safety incidents and failures. Individuals and organizations looking to bolster their safety investments can get their biggest bang for their buck by starting with these human factor best practices.

- Seek specialized expertise of qualified engineers and technically diverse teams.
- Technical training and knowledge of operators/owners.
- Having decision makers develop a comprehension of risk.
- Embrace the need for continuing education in all engineering disciplines.

Useful References

[1] Independent Forensic Team Report – Oroville Dam Spillway Incident, January 2018.

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Human Factor Best Practices to Achieve Safety[1]

General Design Features	Organizational & Professional Practices		Warning Signs
- Identification and application of accepted best practices. - Design conservative safety margins in line with uncertainties and risks. - Redundancy, robustness, and resilience. - Progressive and controllable failure with warning signs, including accurate hazard classification and emergency action planning. - Customization to project sites, including scenario planning during design and testing/adaptation during construction. - Budget and schedule contingencies should be included.	- Sufficient budget and staffing resources. - Internal organizational diversity and capability for challenge response. - Recognizing limitations of knowledge and skills and defer to expertise. - Learn from past mistakes. - Cognitive diversity within teams for different perspectives, education, skills, experience, etc. - Decision-making authority in line with responsibilities and expertise. - Safety culture & safety-oriented personnel selection.	- Peer review & cross-checking - Information sharing (allowing dissent) to 'connect the dots', including thorough documentation - Diverse teams, but with leadership, continuity, and avoiding 'diffusion of responsibility' - Use of customized checklists. - Appropriate system models (possibly including human factors) and failure modes, and careful software use. - Organized and readily available documentation. - Professional, ethical, and legal/regulatory standards. Including the Professional responsibility to work within an individual's area of expertise.	- Look for them actively and monitor, including after unusual events - Investigate to understand their significance - Address promptly and properly, with verification of follow-up - Be suspicious during 'quiet periods'
Adequate technical training and continuing education including learning from failures and incidents			

1. *Adapted from the Human Factors in the Oroville Dam Spillway Incident – ASDSO Webinar, Presented by Irfan A. Alvi, PE, Alvi Associates, Inc.*

Abandonment of Low-Level Outlet Conduits…Think it Through Before you Grout it Through

By: Richard F. Walker Jr, PE

Introduction

Deterioration of low-level outlet conduits is a common problem, especially for older embankment dams. When the existing conduit deteriorates to a point where it can no longer serve its intended design purpose, a decision must be made to rehabilitate, remove and replace, or abandon it.

Removal and replacement is the most reliable approach, but will most likely require draining of the reservoir and result in the highest cost to the owner. Rehabilitation can be a reasonable alternative and is typically accomplished by one of two methods, sliplining or cured-in-place pipe (CIPP) liners; however, it may not be applicable for severely deteriorated conduits (See Figure 1) or changes in loading conditions.

In some cases, the owner and/or designer may find it technically and economically more feasible to install a new alternate means of water conveyance and abandon the conduit by grouting it closed and leaving it in place. The advantages of abandoning an existing conduit through an embankment dam include:

- *Excavation*—A large excavation is not required through the embankment dam.
- *Reservoir operation*—Abandonment can in some cases be done while the reservoir is full.
- *Costs*—Costs are generally less than other rehabilitation and replacement methods.

The disadvantages of abandoning an existing conduit through an embankment dam include:

- *Grouting*—Difficulties may be encountered while trying to fill the existing conduit with grout.
- *Loss of use*—A replacement means of providing downstream flow and flood discharge capacity will be required.

The most common way to abandon an existing conduit is by backfilling with grout or concrete. Owners of dams with release requirements may choose to abandon the existing conduit after installing a new one in a new location. In embankment dams with small reservoirs and no regulation or requirements on regular water flow or release, an abandoned conduit's function can be accomplished by an alternative means of water conveyance, such as a siphon or high-level outlet conduit.

This article will focus on abandoning conduits without replacement in-kind for small-sized dams. Information is presented on alternatives for water conveyance, the implications of abandoning a conduit in-place, and the means and method of abandoning the conduit.

Figure 1. Severely deteriorated CMP outlet conduit. [4]

Figure 2. Typical drop-inlet structure for outlet conduit.

Dam ownership, regulation, and operation vary from the federal government, state government, local municipalities, utility providers, and in some cases private individuals or group owners. Because no two dams are the same and their ownership, operations, obligations, and impacts are very specific to their individual circumstances; this article will discuss these topics in generalities.

Articles in previous issues of Western Dam Engineering Technical Note have discussed methods for rehabilitation and replacement of outlet conduits and are referenced below:

- *Volume 1: Issue 1 – "Low-Level Conduits – Rehab or Replace?"*
- *Volume 2: Issue 2 – "You Con-du-it; How to Fix a Leaky Pipe"*
- *Volume 4: Issue 1 – "You Down with CIPP? – Yeah! You Know Me!"*
- *Volume 5: Issue 2 – "Cellular Grout Use in Conduit Sliplining"*

Alternatives for Water Conveyance

For cases where rehabilitation or replacement in-kind is not an option, alternative means of water conveyance should be designed and installed prior to abandonment of the conduit.

The selection of a means that is appropriate depends on the size of the reservoir, the physical features of the particular dam site, the availability of equipment and materials, the volume of water that may need to be released, and the required rate of release. Care should be employed in determining the means of reservoir evacuation during a specific emergency, to ensure that the reservoir releases do not cause loss of life or significant property damage downstream.

The preferred and recommended method is to install a new low-level outlet. In situations where this is not feasible, installation of a siphon or high-level outlet conduit may be able to provide an alternate means of water conveyance that meet the operational needs and requirements of the dam. Requirements of the design shall include at a minimum: accommodating the desired range of releases, protecting against accidental overfilling, controlling normal reservoir level, and providing for emergency drawdown. Combining a high level outlet or siphon with an auxiliary spillway and/or overflow spillway may be used or needed to meet the requirements of the reservoir.

Each method has its own advantages and disadvantages. The long term performance of the final selection and public safety considerations, rather than cost, should be the basis for the selected design.

Installation of a Siphon

Siphons can often provide alternative reservoir drawdown capability for low hazard dams. A siphon is generally installed over the dam or spillway, providing a safe and easily constructible, but usually temporary, outlet option for dam owners (See Figures 3 and 4).

Figure 3. Siphon used to lower the reservoir water surface through the upper entrance of an outlet works intake structure. [1]

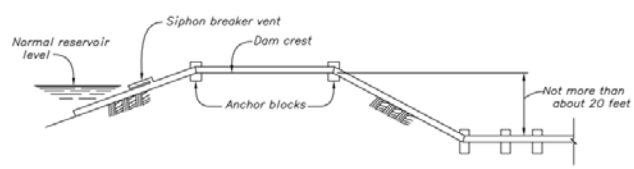

Figure 4. A simple siphon constructed over the crest of an embankment dam. [1]

Siphons used in reservoir drawdown operate by atmospheric pressure pushing water over an obstacle (i.e., reservoir water over an embankment dam) and discharging on the other side at a lower elevation than the reservoir. The maximum height, or lift, of a siphon is limited by the atmospheric pressure at the site. The height a siphon can lift water will, therefore, be lower for dams at higher elevations (for instance in the mountains of the western United States). There are several parameters that must be evaluated when establishing the feasibility and design of a siphon. Bernoulli's equation can be applied to estimate a siphon's maximum lift, discharge capacity, diameter, and pressure.

Siphons require a priming method to initiate siphon action. Multiple methods can be considered such as vacuum pump, water pump, or hand pump. Siphons can also be designed to be self-priming so mechanical means are not necessary to fill the pipe to initially start siphon action to drawdown the reservoir. One way this can be accomplished is by designing the siphon system so when water level rises to emergency spillway level, air is expelled from the system starting full pipe flow. A self-priming siphon may require excavation into the embankment to locate it below the anticipated reservoir water level.

Provisions for breaking the siphon (siphon breaker vent) should be provided at the crest of the embankment, should the need arise. Self-priming siphons will not stop until the siphon process is broken either by mechanical means (human intervention) or until the water level in the reservoir reaches the level of the siphon intake.

The advantages of a siphon include:

- Reservoir does not have to be completely drained.
- Installation of siphons can be performed in a relatively short amount of time and are typically cost-effective.
- Specialty contractors are not required if quality engineering oversight is available during construction.

The disadvantages of this option include:

- Some excavation of the dam may be required. If the dam crest is utilized as either a pedestrian path or vehicular path, some interruption of service should be anticipated.
- A pump is required to initiate flows unless a self-priming siphon is installed.
- Inefficient removal of water at heads below 1 to 1-1/4 times the diameter of the pipe, which causes excessive fluctuations in the water surface when compared to pipe and riser spillways.
- Not cost-effective for large reservoirs and watersheds.
- Can be susceptible to vandalism, unless protective measures are taken.
- Limited ability to drain reservoir deeper than 20 to 25 feet.

In some situations, equipment for the siphon or pumps can be procured and stored at the dam with the intent of quickly installing the siphon temporarily for use during emergencies or as needed. This option must be carefully evaluated and may only be applicable for circumstances where a smaller-sized dam is located off-channel (i.e., not on a live stream) and thus would not invoke the need to release water frequently or at high rates.

Contingency plans should be made during the design process, which outline actions to take in the event that the capacity of diversion measures is exceeded. Such plans should include a notification list of State dam safety program staff, emergency management officials, and other State and local representatives, who can assist in the event of an emergency.

For readers needing more information about siphons, a detailed discussion of design, installation and operation of siphons was presented in Volume 1: Issue 1 of Western Dam Engineering: Technical Note – "Simple Steps to Siphoning."

A case study of problems encountered and lessons learned with the installation of a new siphon at Crossgate Dam in Raleigh, North Carolina, is presented in the paper, "To Siphon or Not To Siphon: That is the Question (Among Others) A Repair History of Crossgate Dam Raleigh, NC."

Installation of a High-Level Outlet Conduit

Installation of a high-level outlet conduit is similar to a traditional low-level outlet conduit but requires significantly less excavation or disturbance to the dam or reservoir operations. It typically involves installing a weir-box or stop-log structure into the dam embankment with the invert set at a higher elevation than the low level outlet. Common conduit materials used are reinforced concrete (cast-in-place or precast), metal pipe (steel, ductile iron, or cast iron)[2], PVC, and high density polyethylene (HDPE). The appropriate material depends on loading (strength) requirements, pipe diameter, and other considerations including constructability, durability, and cost.

[2] Note that corrugated metal pipe [CMP] is not recommended due to the potential of corrosion

Directional drilling methods are sometimes proposed for installation of high-level outlet conduits. These are typically not allowed due to unavoidable disturbance of the soils surrounding the carrier pipe. This disturbed zone creates a seepage path that must be mitigated, which is often difficult and can add significant cost.

The main advantage of this system is its ability to simulate the hydraulic characteristics and efficiencies of the outlet conduit systems located through the base of the dam. Unlike the siphon, this option can be designed to accommodate a wide variation in base flows into the reservoir without the corresponding large fluctuations in reservoir level.

The advantages of such a system include the following:

- Limited embankment excavation
- Limited lake level fluctuation, as compared to a siphon spillway.
- Can be installed without complete draining of the reservoir.
- Cost-effective in that the components are typically small in size and length.
- A stop-log structure, or gate, can be installed to maintain a desired normal high water level and to allow incremental releases for water rights administration.

The system does have disadvantages, such as:

- Cannot be utilized to drain the reservoir below the invert elevation of the intake. Complete draining of the reservoir is not feasible with this system.
- Utilization of this system may require the use of bends or elbows along the conduit to allow for the discharge of water at or near the downstream toe. Conduit bends/elbows can be expensive. It may just require a downstream conveyance channel be excavated and adequately armored against erosion.
- Foundation soils for the intake may be soft, which can cause settlement problems or raise costs due to over-excavation.
- The height of fall in the conduit is limited. Pipe or culvert spillways should not be used for drops from riser invert to pipe outlet greater than about 25 feet, due to the danger of cavitation.

Design and construction guidance on approach, entrance and terminal structures, and discharge channels, control features, and gate chambers supporting the high-level outlet conduit are outside the scope of this document. Additional guidance relating to various components of an outlet works is available in references, such as Reclamation's *Design of Small Dams* (1987a), and USACE's *Structural Design and Evaluation of Outlet Works* (2003b) and *Hydraulic Design of Reservoir Outlet Works* (1980).

Implications

Abandonment of low-level outlet conduits has significant implications on the operations of the dam, including the ability to drawdown the reservoir or make water releases.

The reasons for water releases can vary widely based on the purpose of the dam. Dams are built for a variety of purposes including irrigation supply for agriculture, municipal water supply for communities, power generation, storage and attenuation of water during high precipitation or snow melt, to develop/restore various types of ecosystems, recreation, or combinations of all of these purposes.

The purposes, schedules, rates, and magnitudes of regular (normal-operation) water releases are generally described in a dam's Operation and Maintenance Manual (O&M). Water releases can occur for recreation, environmental considerations, and water rights and water supply administration.

In addition to water release requirements under normal operations, reservoir drawdowns may also be periodically required for maintenance, emergency operations, or in advance of predicted floods. Drawdowns mandated by Dam Safety regulatory agencies can be driven by poor operating conditions or damage to the dam, stability concerns, design issues, maintenance, or repairs.

All dams are, or should be, equipped with outlet structures or systems for releasing water. Dams can be outfitted with different combinations of discharge structures with varying degrees of redundancy. Low-level outlets provide a means of controlled reservoir release and drawdown below the invert of other discharge structures. A low-level outlet system is used to dewater a reservoir for inspection or construction activities or in the case of emergencies, and can also support regular water releases as summarized below.

The following are possible reasons or needs for water release that may be impacted by conduit abandonment:

1. Supply – Downstream releases to supply irrigation canals, pump stations, water treatment plants, and recreational waterways.
2. Water Rights Administration – Releases to satisfy downstream senior water right calls, out-of-priority storage and/or augmentation of evaporative losses.
3. Seasonal Operation –Provide storage space prior to seasons of high precipitation and/or snow melt runoff.
4. Flooding – Release of water stored during infrequent but significant precipitation events to reduce peak flood discharge downstream. After the event, the reservoir is lowered at a controlled rate to normal operating level.
5. Sediment Flushing – Scheduled releases to flush sediment to manage undesirable sediment accumulation.
6. Environmental/Biological – Releases to benefit downstream ecology and habitat.
7. Inspections, Repairs, & Modifications –Provide safe reservoir levels to inspect, repair, or construct modifications to dams.
8. Damage/Distress – Emergency evacuation of reservoirs as fast as safely possible to reduce risk of failure in case of damage to dams during extreme events or emergencies.

The decision to abandon the low-level outlet conduit without replacement results in the loss of all of the above functionality, which can prove to be detrimental in an emergency. Outlet abandonment may also result in more frequent use of the primary, auxiliary, or emergency spillways. More frequent operation of the spillway structure(s) may be undesirable as compared to passage through the outlet or lowering the reservoir level in advance of flooding by a controlled operation. Low-level outlet abandonment may alter the flood capacity of the reservoir and have impacts on the communities and environments both upstream and downstream from the dam.

For the reasons listed above, abandonment of a low-level conduit without in-kind replacement is typically only applicable to smaller sized dams with no minimum flow or release requirements. The owner/designer should evaluate carefully the hydraulic impacts, effects of loss of use on operations, and needs for alternative water conveyance as a result of loss of use of the low- level conduit. Furthermore, the advantages of leaving the conduit in place must be weighed against the concerns of creating possible seepage paths, which could cause future problems, and continued conduit deterioration.

For more information on the needs and considerations for low-level outlet conduits, see the previous Western Dam Engineering Technical Note article Volume 2 Issue 3: "How Low Can You Go? The Needs and Considerations for Outlets."

Means and Methods of Abandonment

The most common method to abandon an existing conduit is by backfilling with grout or flowable concrete. This method is discussed in more detail in the following paragraphs of this article. Detailed information on conduit abandonment by grouting is provided in the FEMA Technical Manual, *Conduit through Embankment Dams*.

Two methods are usually considered for backfilling with grout:

- **From upstream, downstream or center access**—If conduit access is available from either upstream, downstream or center locations, these typically provide the simplest method for filling with grout or concrete. Removal of a portion of the entrance, terminal or center control structures may be required to attain sufficient access.
- **Through holes drilled from the surface of the embankment dam**—When the upstream and downstream ends of the existing conduit are inaccessible and there is no center control structure, it may be possible to fill the conduit with grout or concrete through holes drilled from the surface of the embankment dam (Figure 5). To be successful, the precise location of the existing conduit must be determined, and the driller must be experienced and proceed with caution.

Figure 5. Abandonment of a conduit by cement grout through holes drilled from the surface of the embankment dam to depths of up to 60 feet. [1]

Completely filling the existing conduit is recommended. Partial filling of an abandoned conduit would need to be evaluated and consider long term safety (failure mode) concerns. The indicated grouting and backfill procedures in this section may require modification to adapt to given site conditions. The designer is cautioned that grout from the surface, unless carefully controlled, has the potential for causing hydraulic fracture within the embankment dam. Drilling from the surface of the embankment dam is not advisable for situations where the reservoir water surface cannot be lowered.

Drilling Into Existing Embankment Dam

Drilling into an embankment dam can cause serious damage and the need to do so should be carefully considered. If drilling into an embankment dam has been determined to be necessary, drilling through any portion of an embankment dam should be performed with extreme caution. Improper drilling procedures increase the potential for hydraulic fracture. Drilling fluids, such as water or bentonite, are sometimes used during drilling to enhance removal of drill cuttings, but these fluids should be avoided when drilling in embankment dams.

Auguring is the preferred method for drilling in the core of embankment dams. Auguring uses no drilling fluid and is inherently benign with respect to hydraulic fracturing. A hollow-stem auger permits sampling in the embankment and foundation through the auger's hollow stem, which acts as casing. If fluids must be used, the risks must be understood and specific procedures should be employed to minimize the chance for hydraulic fracturing.

For more information on drilling into existing embankment dams, see the previous Western Dam Engineering Technical Note article Volume 2 Issue 1: "Poking the Bear: Drilling and Sampling for Embankment Dams."

Inspection

A thorough inspection of the existing conduit is required prior to beginning any abandonment activities. Depending on the diameter of the conduit, man-entry or CCTV inspection methods should be used. The condition of the existing conduit, existence of any defects, protrusions or obstructions, joint offsets, amount of deflection, and evidence of leakage or internal erosion should be determined.

A detailed discussion about inspection of conduits was presented in Volume 2: Issue 2 of Western Dam Engineering Technical Notes: "You Con-du-it; How to Fix a Leaky."

Preparation

The existing conduit surfaces against which grout will be placed should be free of roots, sediments, mineral deposits, dust, laitance, loose or defective concrete, curing compound(s), coatings, and other foreign materials. Any sediment or debris should be removed from the invert of the existing conduit. Where possible, any bolts or other projections should be cut flush and ground smooth with the interior surface of the existing conduit.

Abandonment of the existing conduit may need to be scheduled to allow grouting operations when the reservoir is at its lowest annual elevation. Siphons or pumps can be used to further reduce reservoir elevations. In some cases, the construction of a cofferdam may be more applicable if the reservoir water level needs to remain at a constant elevation. If a new conduit is being constructed, grouting of the existing conduit can be delayed until the new conduit can be used for diversion.

For accessible existing conduits, any open or leaking joints or holes should be patched to minimize grout leakage. An engineered bulkhead should be installed at the downstream end of the existing conduit to resist the loadings from the grout or concrete. An air return (vent) pipe or a series of pipes should be installed at the crown of the conduit and extend from the upstream end of the conduit to the bulkhead. Grout pipes should be installed at the crown of the conduit. Grouting equipment should be capable of continuously pumping grout at required pressures.

Abandoning an inaccessible existing conduit is much more problematic due to the lack of access into the interior of the conduit. Stopping the flow of water into the existing conduit may be difficult, if there is an opening through the conduit. Abandonment may be possible by drilling into the conduit from the surface of the embankment dam at several locations and pumping a thick sand and grout mix (sometimes referred to as compaction grout, limited mobility grout, or LMG) to form a bulkhead.

This technique was successfully used to stop leakage in a deteriorating conduit through a 65-foot-high embankment dam in southern Maryland. In this case, the approximate location of the conduit was first established by use of several geophysical methods (magnetometer, resistivity, and self-potential). An experienced driller was able to detect when the drill bit entered the existing conduit, advanced it to the middle of the conduit, and then pumped the grout to form the bulkhead. Grout was tremied into the existing conduit through additional holes drilled from the surface of the embankment dam.

Filter Diaphragm or Collar

If abandonment is selected, a filter diaphragm or collar should be part of a design to intercept any flow that could potentially occur through defects in the grouted conduit or along the interface between the existing conduit and earthfill. For guidance on the design of filter diaphragms and collars, refer to Chapter 6 of the FEMA Technical Manual, *Conduit through Embankment Dams*. Design of the filter diaphragm or collar would need to be modified from standard designs and located further downstream to limit excavation.

Grouting

- **Grouting plan—**A grouting plan detailing the contractor's proposed grout mix equipment, setup, procedures, sequencing, plan for handling waste, method for communication, and method for sealing and bulkheading upstream and downstream should be submitted for review by the Designer prior to initiation of grouting operations.
- **Grout and concrete mixes—**Use a grout mix with water (ASTM C 94) to cement (ASTM C 150) ratio of approximately 0.7:1 to 0.5:1 by weight. A grout fluidifier (ASTM C 937) may be needed to promote flowabilty, reduce water requirements, reduce bleeding, reduce segregation, increase strength, and eliminate grout shrinkage during setting of the grout mix. Trial mixes should be mixed at the job site prior to grouting to confirm the expected performance of the mix. For concrete backfill, the aggregate size should be selected based on the specific application but should not exceed 3/4 –inch. A 28-day compressive strength of 3,000 lb/in^2 is generally acceptable.
- **Procedure**—Install bulkhead (if applicable) prior to sealing. Sealing the conduit with grout or concrete is typically completed in two stages: 1) backfill grout or concrete (pump conduit full of concrete under low pressure [not to exceed 5 psi]) and 2) contact grouting (pumping grout along the inside crown of the pipe under higher pressure [not to exceed 25 psi]) to fill voids left by stage 1. Stage 2 is not typical for low-head dams. Especially where deterioration could allow the pressures to impact the embankment around the conduit.
  Assuming only Stage 1 is required; the pressure at the crown of the conduit as measured at the vent pipe should not exceed 5 psi. Grouting is stopped when the air return pipe in the crown flows full with grout. Cap the grout and air return pipes. Remove the bulkhead upon completion of grouting operations. For grouting or backfilling of long existing conduits, the use of sections is recommended. Long grout or backfill placements could result in expansion and/or contraction of the grout that could induce cracking of the existing conduit (concrete). The use of sections is also conducive to ensuring an acceptable seal of the conduit. Figures 6 and 7 show grouting operations

involved with the abandonment of an outlet works conduit.

Figure 6. Abandonment of a conduit by pumping cement grout through holes drilled from the surface of the embankment dam to depths of up to 60 feet. [1]

Figure 7. Grout being delivered to the pumping truck. [1]

Summary

Abandonment of low-level outlet conduits may be an option if the following apply to your dam:

- ✓ The results of an inspection of a low-level outlet conduit reveal damage that could lead to a future "incident," repair or replacement alternatives are prohibitive, and abandonment methods cannot cause harm.
- ✓ There are no regulations or requirements for regular water flow or release. Regular control of the reservoir level is not considered a critical feature in the performance of the dam.

If the above two conditions apply then the following also needs to be considered to adequately manage risk for water conveyance in an unusual or emergency event:

- ✓ Are there alternate means for water conveyance during flood or emergency events? If the dam is on a live stream, this is a must!
- ✓ If the dam is off-channel:
  - o Is it feasible to install a new permanent siphon or high-level outlet?
  - o Is it feasible to quickly install pumps and/or temporary siphon to handle water conveyance requirements?
  - o Can inflows be controlled?

Low-level outlet abandonment is usually not a viable option for larger or high hazard dams. The owners and operators should fully understand the implications of loss of use of the low-level outlet. Alternative methods of water conveyance should be provided as described in this document prior to abandonment of the existing outlet.

Abandonment of a low-level outlet is typically done by fully filling the conduit with grout or concrete and should be conducted in accordance with best practices as outlined in Chapter 14 of the FEMA Technical Manual, *Conduits through Embankment Dams*.

The designer should consider replacement, rehabilitation, and abandonment alternatives carefully and understand that each project site may have specific challenges that need to be considered.

FEMA's technical manuals provide detailed discussion of parameters that should be considered during the conduit abandonment design process. They also contain detailed discussion on repair and replacement of conduits.

FEMA - *Conduits through Embankment Dams*
FEMA - *Plastic Pipe Used in Embankment Dams*

Useful References

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