From:	Miller, Ed
To:	"RILEY, Jim"
Subject:	Comments on Dam Failure White Paper
Date:	Friday, August 17, 2012 8:56:00 AM
Attachments:	Dam Failure August 8 2012.docx

Jim,
Attached is the track-changes version that contains the comments from the public meeting.

Ed Miller
415-2481

POST-FUKUSHIMA NEAR-TERM TASK FORCE RECOMMENDATION 2.1
Supplemental Guidance for the Evaluation of Dam Failures

Comment [g1]: Recommend add section numbers

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A. Background

In response to the nuclear fuel damage at the Fukushima-Daiichi power plant due to the March 11, 2011 earthquake and subsequent tsunami, the United States Nuclear Regulatory Commission (NRC) is requesting information pursuant to Title 10 of the Code of Federal Regulations, Section 50.54 (f) (10 CFR 50.54(f) or 50.54(f)). As part of this request, licensees will be required to reevaluate flooding hazards, per present-day guidance and methodologies for early site permits and combined license reviews, to assess margin at safety-related structures, systems, components (SSCs) and effectiveness of current licensing basis (CLB) protection and mitigation measures. The request is associated with the NRC's Post-Fukushima Near-Term Task Force (NTTF) Recommendation 2.1 for flooding, approved by the Commission in SECY 11-0137, *Prioritization of Recommended Actions to be Taken in Response to Fukushima Lessons Learned*, dated December 15, 2011.

- **Summary of Requests in the March 12, 2012 50.54(f) Letter**

  Requested Action:

  - Evaluate all relevant flooding mechanisms using present-day regulations, methodologies, engineering practices, and modeling software (Phase 1). Actions associated with Phase 2 (above) are not being requested at this time, pending completion of the Phase 1 evaluations.
  - Where the reevaluated flood exceeds the design basis, submit an interim action plan that documents actions planned or taken to address safety issues (if any) at the new hazard levels.
  - Perform an integrated assessment of the plant for the entire duration of the flood conditions to identify vulnerabilities and corrective actions under full power operations and other plant configurations. The scope also includes those features of the ultimate heat sinks that could be adversely affected by flood conditions and lead to degradation of the flood protection. (The loss of ultimate heat sink from non-flood causes is not included.)

  Requested Information:

  - Hazard Reevaluation Report – Documents the results of the new evaluations for all relevant flooding mechanisms.
  - Integrated Assessment Report – Documents corrective actions (completed and/or planned) for plants where the current design basis floods do not bound the reevaluated hazard for relevant mechanisms and the entire duration of the flood.

- **Flooding Evaluation Guidance**

  Prior to the March 2011 Fukushima-Daiichi earthquake/tsunami events, the NRC standard for flood estimation was the 1977 version of Regulatory Guide (RG) 1.59 and its appendices:

  ~~A. Probable Maximum and Seismically Induced Floods on Streams and Coastal Areas (which references American National Standards Institute (ANSI) Standard N170-1976, superseded by ANSI/ANS (American Nuclear Society) 2.8, "Determining Design Basis Flooding at Power Reactor Sites", July 28, 1992)~~

  ~~B. Alternative Methods of Estimating Probable Maximum Floods~~

  ~~C. Simplified Methods of Estimating Probable Maximum Surges~~

Comment [g2]: Recommend describe phase 1 and phase 2

Comment [g3]: Include whole requested information list from 10 CFR 50.54(f) letter

Comment [g4]: Reference Standard Review Plan in effect at time of issuance of 10 CFR 50.54(f) letter

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In the 50.54(f) letter, the NRC is requesting updated flooding hazard information using 'present-day regulatory guidance and methodologies to review early site permits (ESPs) and combined license (COL) applications'. Although the update to RG 1.59 is not complete, the NRC is considering NUREG/CR-7046, "Design Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America", November 2011, as representing present-day methodologies for flooding evaluations; ~~superseding Appendix A of RG 1.59 (ANSI/ANS 2.8).~~

NUREG/CR-7046 describes present-day methodologies and technologies that can used to estimate design-basis floods at nuclear power plants for a range of flooding mechanisms, including rivers/streams, dam failures, local intense precipitation (local/site runoff), storm surge, seiche, ice-induced flooding, channel migration/diversion, and combined-effects floods (for dependent or correlated events).

~~Note that NUREG/CR-7046 does not address tsunamis;~~ NUREG/CR-6966 ("Tsunami Hazard Assessment at Nuclear Power Plant Sites in the United States of America") is referenced as a guide for the evaluation of tsunamis.

- **Deterministic versus Probabilistic Approaches**

NUREG/CR-7046 provides only an introduction to the application of probabilistic methods in flood estimation at nuclear power plants, acknowledging that detailed methodology and guidance are currently not available. For flooding hazard reevaluations, deterministic methods should be used. Probabilistic methods may be included to establish a relationship between flood magnitude and exceedance probability in developing the Integrated Assessment, required if the reevaluated flood hazard is not bounded by the current licensing basis.

Comment [g5]: There is limited experience on doing probabilistic floods. Significant NRC review would be expected.

- **Hierarchical Hazard Assessment (HHA) Approach**

NUREG/CR-7046 describes the Hierarchical Hazard Assessment (HHA) approach as:

> "a progressively refined, stepwise estimation of site-specific hazards that evaluates the safety of SSCs with the most conservative plausible assumptions consistent with available data. The HHA process starts with the most conservative simplifying assumptions that maximize the hazards from the probable maximum event for each natural flood-causing phenomenon expected to occur in the vicinity of a proposed site. The focus of this report is on flood hazards. If the site is not inundated by floods from any of the phenomena to an elevation critical for safe operation of the SSCs, a conclusion that the SSCs are not susceptible to flooding would be valid, and no further flood-hazard assessment would be needed."

The HHA process allows licensees the option to conduct simplified flooding evaluations, based on varying degrees of conservativeness, to assess susceptibility to flooding. The evaluation is refined using site-specific parameters to achieve a realistic, physics based, but conservative analysis of flooding, particularly when resulting hazard levels exceed acceptance criteria for safety-related SSCs. NUREG/CR-7046 describes the key steps in the process as follows:

1. Identify flood-causing phenomena or mechanisms by reviewing historical data and assessing the geohydrological, geoseismic, and structural failure phenomena in the vicinity of the site and region.
2. For each flood-causing phenomenon, develop a conservative estimate of the flood from the corresponding probable maximum event using conservative simplifying assumptions.

3. If any safety-related SSC is adversely affected by flood hazards, use site-specific data to provide more realistic conditions in the flood analyses~~ while ensuring that these conditions are consistent with those used by Federal agencies in similar design considerations~~. Repeat Step 2; if all safety-related SSCs are unaffected by the estimated flood, or if all site-specific data have been used, specify design bases for each using the most severe hazards from the set of floods corresponding to the flood-causing phenomena.

- **Dam Breaches and Failures**

  Mechanisms that cause dams to fail include overtopping of an unprotected portion of the dam during a significant hydrologic event, piping, liquefaction of foundation from seismic activity, slope/stability issues, uncontrolled seepage, and other deficiencies. The resulting flood waves, including those from domino-type or cascading dam failures, should be evaluated for each site as applicable. Water storage and water control structures (such as onsite cooling or auxiliary water reservoirs and onsite levees) that may be located at or above SSCs important to safety should also be evaluated. Acceptable models and methods used to evaluate the dam failure and the resulting effects should be appropriate to the type of failure mechanism. References provided herein include acceptable guidance documents to developing dam break hydrographs. Unsteady-flow (e.g. HEC-RAS) or 2D hydraulic models are frequently used to route dam breach hydrographs to the site. Recent analyses completed by ~~State and Federal Agencies~~entities with appropriate jurisdiction for dams may be incorporated into the analysis~~used~~. Dam breach/failure scenarios should include coincidental failure with the peak PMF and domino-type or cascading dam failures unless an engineering justification is provided showing that a failure mode is not credible as part of the refined site specific hazard analysis. Part of the HHA approach may include an assumption that all dams fail, regardless of the cause; timed to produce the worse possible flooding conditions at the site (including compounding flows from cascading failures of dams in series).

B. Scope and Purpose

This paper is intended to clarify how dam failure should be considered when reevaluating the bounding PMF in response to Enclosure 2 (Recommendation 2.1: Flooding) of the March 12, 2012 50.54(f) letter. This paper provides added detailed guidance to supplement the NUREG/CR-7046, Sections 3.4 and 3.9 and Appendix H.2, related to dam failure considerations. The goal is to achieve a realistic, physics based, but conservative analysis of flooding. The following is a summary of ~~guidance provided in NUREG/CR-7046~~definitions:

Comment [g6]: Define each failure mechanism

- **Hydrologic Upstream Dam Failure:** PMF hydrographs, generated from PMP scenarios discussed previously, should be routed through upstream dams using the USACE HEC-HMS (or equivalent) model. If the model indicates that one or more dams are unable to safely pass the PMF (i.e. the PMF hydrograph overtops an unprotected portion of the dam(s)), the dams should be breached to coincide with the peak of the PMF. Dams in series should be breached as cascading failures.
- **Seismic Upstream Dam Failure:** NUREG/CR-7046, Appendix D states that "dam breach usually refers to a structural failure of the embankment that may be caused by a hydrologic event (e.g., overtopping of a dam during a flood, leading to erosion of the dam face or piping and resulting in erosion of the embankment) or a seismic event". Seismic events are not expected to occur coincidently with a large hydrologic event. It is also expected that large hydrologic events (i.e., the PMF) bound the seismic events since release of stored water impounded by the dam during the PMF would be greater than during the seismic event; although, the seismic event may produce the

bounding warning time. The methods for evaluating a seismic failure are per Appendix H.2 of NUREG/CR-7046. The following seismic/precipitation combinations should be considered:

1. Safe shut-down earthquake (SSE) and 25-year precipitation.
2. Operational basis earthquake (OBE) and ½ PMP or 500-year precipitation, whichever is less.

- **Sunny Day Upstream Dam Failure:** A 'sunny day' dam failure is typically not associated or concurrent with an extreme flood and may occur due to failures of embankment material or foundation, such as those due to piping through the embankment. 'Sunny day' failures would normally not exceed flood magnitudes resulting from the hydrologic and seismic failure scenarios discussed above. However, it is recommended that the affects of a 'sunny day' failure be considered particularly when mitigation measures protect safety-related SSCs from such a failure, given the more limited warning time generally associated with a 'sunny day' failure.
- **Loss of Ultimate Heat Sink due** to **Flooding-Induced Downstream Dam Failure:** The NRC is requesting that the Recommendation 2.1: Flood Hazard Reevaluations include an evaluation of the effects of flooding on downstream dams that are used to impound the ultimate heat sink (UHS).
- **Security Threats:** It is assumed that failures from modes other than natural hazards (e.g. terrorism) do not need to be considered in the Recommendation 2.1, Flooding Reevaluations.

Comment [g7]: Recommend quoting the ANSI guide instead. ANSI/ANS 2.8-1992, Section 9.2.1.2

Comment [g8]: However a justification for this would need to be provided

Warning time? Assumptions for initial water levels and failure modes?

C. Approach

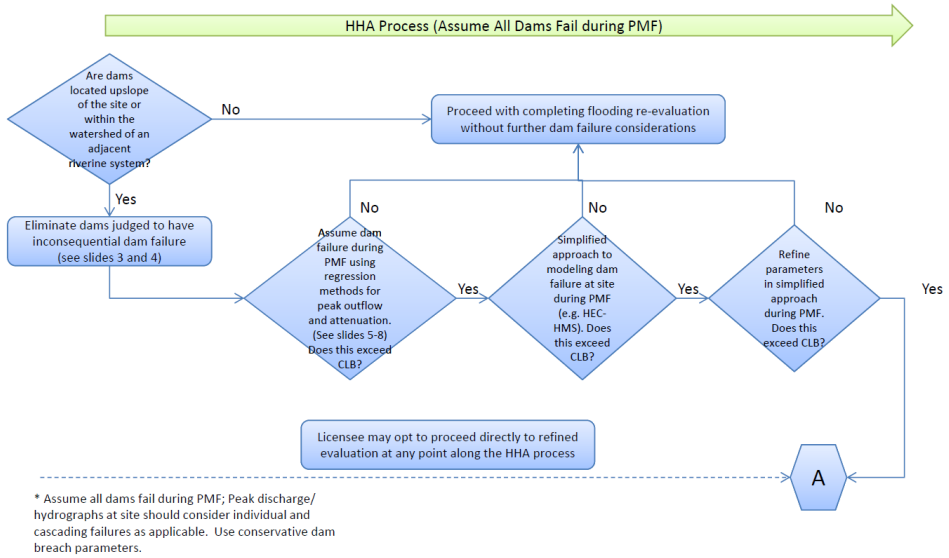
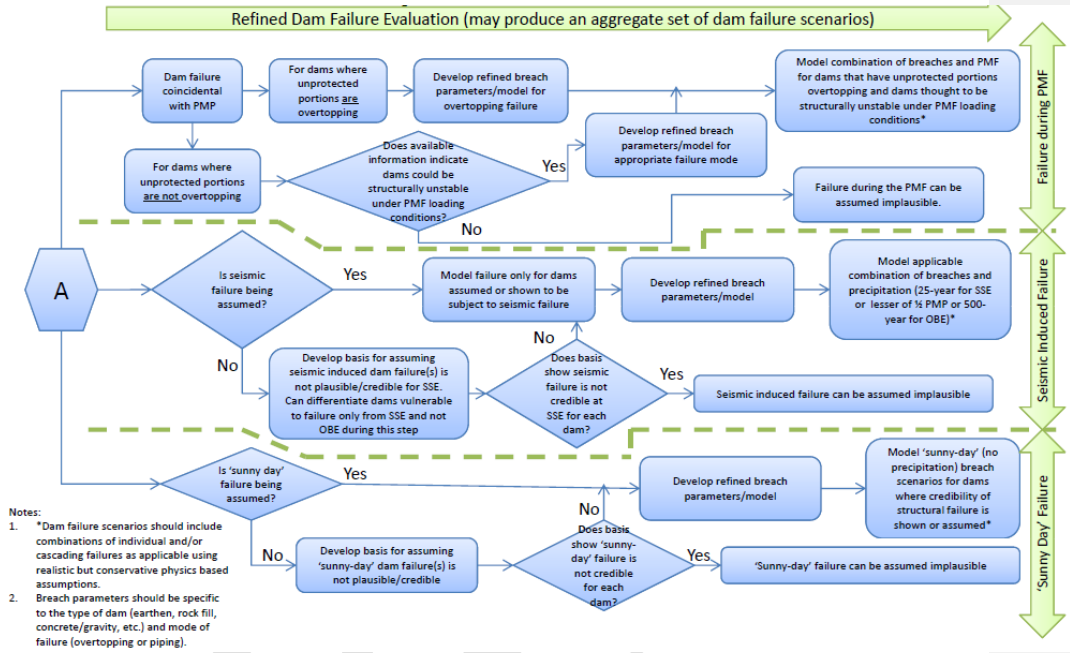


Figure 1 - Dam Failure Process/Decision Flow Chart

Comment [g9]: Dams that are not screened out are assumed to fail



Recommend update flowchart based on subsequent discussions

C.1 Hierarchical Hazard Assessment (HHA) Approach for Upstream Dam Failure

According to Section 3.4.1 of NUREG/CR-7046, 'the simplest and most conservative dam-breach induced flood may be expected to occur under the assumption that (1) all dams upstream of the site are assumed to fail during the PMF event regardless of their design capacity to safely pass a PMF and (2) the peak discharge from individual dam failures reach the site at the same time.' Per Figure 1 (Decision/Process Flow Chart), the HHA approach to dam failure evaluations includes the following possible steps:

1. Eliminate dams judged to have inconsequential dam failure
2. Assume Failure during PMF (using Regression Peak Outflow and Attenuation Estimates)
3. Simplified Modeling of Dam Failure during PMF
4. ~~Refined/Site-Specific Dam Failure Evaluation~~

Eliminate Dams Judged to have Inconsequential Dam Failure

State dam inventories and classification systems can be used to identify dams within the watershed of an adjacent river. Most states use a system to classify the size and hazard potential of each dam that can be used to identify dams that can be eliminated from further consideration (e.g. small, low-hazard dams). The

only exception are dams immediately upslope from the site; failure from even small, upslope dams can have adverse consequences at the site.

When in question, a relationship can be developed between the size of dam (e.g. height) and distance to site to further screen out dams from further consideration. Peak flow and attenuation estimates, discussed further in the next section, can be used to develop a relationship between dam size and distance and establish thresholds for dams with inconsequential failure. For example, use the USBR (1982) equations for attenuation and peak outflow estimates, respectively, as follows:

Comment [g10]: Possibly move to an appendix.

Describe limits of scope of applicability (downstream distance, dam height, etc…) and reflect limits in figure.

Equation 1

Equation 2

Converting the USBR (1982) Q_p equation to English units (where 1 cms = 35.315 cfs and 1 meter = 3.281 feet),

Comment [g11]: What is the definition of Qp

Simplifying,

Equation 3

Substituting Equation 3 into Equation 1,

Equation 4

With a given allowable Q_r (say a certain % of the PMF), the threshold between 'site-specific dam failure warranted' and 'dams having inconsequential impact at site' can be established. Re-arranging Equation 4 to solve for downstream distance from dam (in miles), X,

Comment [g12]: What is the definition of Qr

Equation 5

Equation 5 is plotted on Figure 2 for a range of allowable dam breach peak flow rates at the site, from 1,000 to 200,000 cfs. Figure 2 can be used to further screen consequences of dam failure. With height and location of dams known, from state dam inventories, and the assistance of GIS tools, information can be plotted on Figure 2 to assess the need for site-specific evaluation. For example, it has been established that a nuclear site can accommodate 5,000 cfs from upstream dam failure, in addition to the PMF peak flow rate. According to Figure 2, dams with combinations of distances and dam heights to the right of the 5,000-cfs curve (e.g. 200 miles, 50 feet; 250 miles, 100 feet) can be assumed to have inconsequential affect from dam failure and eliminated from further consideration. Having multiple dams within the same distance range should factor into the allowable peak discharge per dam.

Comment [g13]: Needs further development to address this issue

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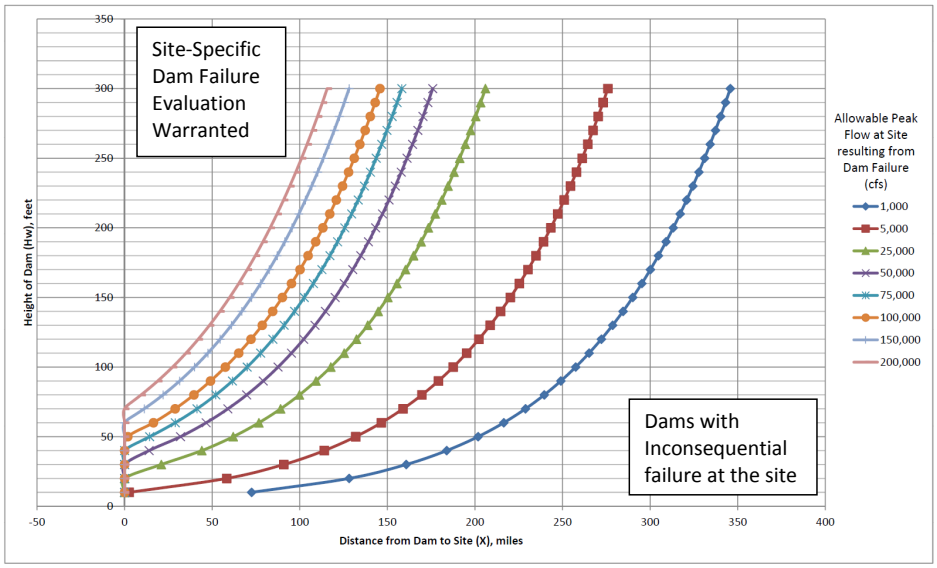

Figure 2 – Distance/Height of Dam Plot

Comment [g14]: Possibly move to an appendix.

Describe limits of scope of applicability (downstream distance, dam height, etc…) and reflect limits in figure.

Assume Failure during PMF using Regression Peak Outflow and Attenuation Estimates

These methods include relatively simple regression equations to estimate the peak outflow and attenuation resulting from a dam failure. Wahl (1998) identified regression equations that estimate the peak outflow discharge as a function of dam and/or reservoir properties based on real dam failure data. Four peak outflow discharge estimation methods are presented below. Note, original technical papers or documentation should be reviewed prior to using these equations to understand their limitations. Wahl (2004) indicates that the Froehlich (1995b) method has the lowest uncertainty of the dam breach peak discharges equations available at the time. Furthermore, Pierce (2010) indicated that the USBR (1982) and Froehlich (1995) equations 'remain valid for conservative peak-outflow predictions' for embankment dams.

- USBR (1982) Peak Outflow (Case Study for 21 dam failures)

Where:

Q_p = Peak breach discharge (cm/sec)

H_w = Height of water in the reservoir at the time of failure above the final bottom elevation of the breach (meters)

- Froehlich (1995b) Peak Outflow (Case Study for 22 dam failures)

Where:

Q_p = Peak breach discharge (cm/sec)

H_w = Height of water in the reservoir at the time of failure above the final bottom elevation of the breach (meters)

V_w = Reservoir volume at the time of failure (m^3)

- National Weather Service (NWS) Simplified Dam Break Model (for dam heights between 12 and 285 feet)

Where:

Q_b = Breach flow + non-breach flow (cfs)

Q_o = Non-breach flow (cfs)

B_r = Final average breach width (feet), approximately 1H to 5H or

$C = 23.4 \times A_s/B_r$

A_s = Reservoir surface area at maximum pool level (acres)

H = Selected failure depth above final breach elevation (feet)

T_f = Time to failure (hours), approximately H/120 or minimum of 10 minutes or

K_o = 0.7 for piping and 1.0 for overtopping failure

V_s = Storage volume (acre-feet)

- Natural Resources Conservation Service (NRCS); formerly the Soil Conservation Service (SCS)

For $H_w \geq 103$ feet, $Q_{max}=(65)H_w^{1.85}$

For $H_w < 103$ feet, $Q_{max}=(1100)H_w^{1.35}$

- But not less than $Q_{max}=(3.2)H_w^{2.5}$
- Nor greater than $Q_{max}=(65)H_w^{1.85}$

When width of valley (L) at water level (H_w) is less than , replace equation $Q_{max}=(65)H_w^{1.85}$ with $Q_{max}=(0.416)LH_w^{1.5}$

Where:

Q_{max} = Peak breach discharge (cfs)

B_r = Breach factor (acre)

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V_s = Reservoir storage at the time of failure (acre-feet)

H_w = Depth of water at the dam at the time of failure; if dam is overtopped, depth is set equal to the height of the dam (feet)

A = Cross-sectional area of embankment at the assumed location of breach (square feet)

T = Theoretical breach width at the water surface elevation corresponding to the depth, H_w, for the equation $Q_{max}=(65)H_w^{1.85}$

L = Width of the valley at the water surface elevation corresponding to the depth, H_w (feet)

As part of the HHA process, attenuation of the peak discharge can be ignored to conservatively account for the affect of the breach at the site. However, the USBR (1982) provides a simplified method for estimating the peak flow reduction as a function of distance to the site (miles). This dam breach peak flow rate at the site can be added to the PMF peak to estimate the combined flooding impact at the site.

Where:

X = Distance downstream of the dam measured along the floodplain (miles)

Q_r = Peak discharge corresponding to distance X (cfs)

Q_p = Peak dam break discharge at the dam (cfs)

Use Hydrologic Model as a Simplified Means of Evaluating Dam Failure/PMF Combination

Riverine systems with upstream dams will, ordinarily, require the development of a rainfall-runoff-routing model (e.g. HEC-HMS, TR-20, etc.) to estimate a watershed's response to the Probable Maximum Precipitation (PMP). Upstream dams, whose failures are judged to affect the site, would normally be included in the model. The final steps of the HHA approach include using this rainfall-runoff-routing model to simulate dam failure and perform hydrologic routing to the site. For the purpose of this paper, the HEC-HMS model will provide the basis for this stage in the HHA process.

While using HEC-HMS for river reach hydrograph routing has advantages, namely numerical stability and minimal data requirements, its ability to accurately routing breach hydrographs is limited. It uses a simplified hydrologic (kinematic wave) routing method, compared to hydraulic (dynamic wave) routing method (such as that used in the HEC-RAS unsteady flow model), to estimate the affects of channel/floodplain storage on hydrograph attenuation and peak flow rates. See Section __ for additional discussion on flood hydrograph routing.

HEC-HMS has the ability to, not only perform river reach routing, but also generate breach hydrograph at the dam given certain breach parameters. Similar to HEC-RAS, HEC-HMS uses forms of the weir and orifice equations to compute breach discharge values for overtopping and piping failure modes, respectively, at

each time step to generate the breach hydrograph. As shown in Figure 3, the dam breach parameters in HEC-HMS include:

- Final Bottom Width (B_b)
- Final Bottom Elevation
- Left/Right Side Slope (Z)
- Breach Weir Coefficient (for Overtopping Breaches)
- Full Formulation Time
- Piping/Orifice Coefficient (for Piping Breaches)
- Initial Piping Elevation
- Failure Trigger

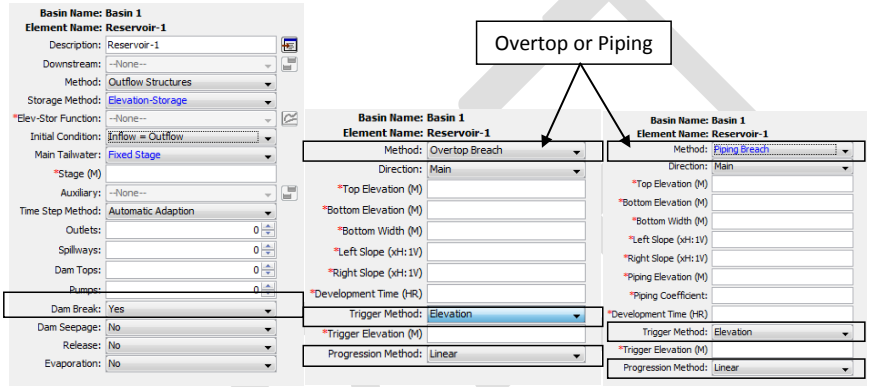


Figure 3- Dam Breach Menu Options in HEC-HMS

Additional information on developing breach parameters is provided in Section C.2. Alternatively, the dam breach hydrograph can be developed outside the rainfall-runoff-routing model and entered as a user-defined hydrograph. For example, the NRCS TR-66 (USDA 1985) provides a methodology for computing outflow hydrographs for overtopping breaches of earthen dams.

Where:

$Q_{t=tn}$ = Peak discharge at time t_n of breach hydrograph (cfs) (see previous section)

Q_p = Peak breach discharge (cfs)

V = Initial storage volume (cubic fee)

t = Time after peak (seconds)

C.2 Refined Upstream Dam Failure Evaluation

Breach Scenarios

Individual and Cascading Failures

Section 3.4 of NUREG/CR-7046 states that "dam failure scenarios, particularly those related to cascading dam failures, should be carefully analyzed and documented to establish that the most severe of the possible combinations has been accounted for. Typically, two scenarios of upstream dam failure should be considered:

1. Failure of individual dams; and
2. Cascading or domino-like failures of dams."

Appendix D, Part D.1, of NUREG/CR-7046 provides additional guidance and examples for developing reasonable individual and cascading failure scenarios. These scenarios should be considered under each of the following failure modes.

~~*Overtopping*~~ *Hydrologic Failure*

The ~~overtopping~~ hydrologic dam failure shall be based on the PMP/snowmelt scenario that produces the bounding PMF at the site. (See Section H.1 of NUREG/CR-7046.) The hydrologic models (i.e. HEC-HMS) used to develop the PMF hydrographs at the site should include routing computations for dams having an attenuation and/or potential dam failure affect at the site. As part of the HHA approach in NUREG/CR-7046, dams can be assumed to fail at the peak reservoir levels, with due consideration to successive or domino dam failures, during the bounding PMP/snowmelt scenario. Conservative breach parameters and simplified routing procedures in HEC-HMS, as discussed in Section __, can be used to assess the impact of this 'total' breach scenario at the site or to evaluate which dam failure(s) is having the greatest affect at the site.

If further refinements are warranted, routing computations in HEC-HMS (or equivalent) can be used to identify dams having 'unprotected' portions overtopping during the bounding PMP/snowmelt scenario. Dams are typically equipped with emergency or auxiliary spillways designed to safely pass extreme flows. 'Unprotected' portions are those that were not designed to pass flow, such as the top of an unarmored earthen dam. Design or as-built drawings of the dam(s) in question should be obtained to understand which portions are protected and designed to pass flow. The refined 'overtopping' failure scenario would included failure of dams shown to have unprotected portions overtopping combined with the bounding PMP/snowmelt scenario; again, with due consideration to successive or domino dam failures.

Seismically-Induced Failure

As stated previously, seismic events are not expected to occur coincidently with a large hydrologic event. It is also expected that large hydrologic events (i.e., the PMF) bound the seismic events since release of stored water impounded by the dam during the PMF would be greater than during the seismic event; although, the seismic event may produce the bounding warning time. The methods for evaluating a seismic failure are per Appendix H.2 of NUREG/CR-7046. The following seismic/precipitation combinations should be considered:

1. Safe shut-down earthquake (SSE) and 25-year precipitation.
2. Operational basis earthquake (OBE) and ½ PMP or 500-year precipitation, whichever is less.

The combinations described in NUREG/CR-7046 are directly from ANS 2.8 (1992), specifically Sections 6.2 and 9.2.1.2, and Regulatory Guide 1.59. As part of the HHA approach in NUREG/CR-7046, a failure of all

Comment [g15]: Begin by discussing individual dam failure, then develop into successive dam failures. Discuss storm centering.

Comment [g16]: Recommend discussion of how to use analyses from other entities (e.g., PMP for an individual dam). Refer back to ANSI 2.8. This discussion may be better placed in another section.

Comment [g17]: Clarify this thought

Comment [g18]: Possibly develop a logic diagram depicting this thought process?

upstream dams under any seismic event and 1/2 PMF, with due consideration to successive or domino dam failures, would produce a bounding scenario. Any postulated breach should be timed to coincide with the maximum reservoir level. To further refine the process, the details described in ANS 2.8 (1992) and RG 1.59 would be required.

Comment [g19]: See previous comment on this wording for water levels during the seismic event

If dams are not assumed to fail from seismic activity, information should be developed to assess a dam's ability to withstand a design earthquake. Regulation 10 CFR 100.23 (d)(3) states "the size of seismically induced floods and water waves that could affect a site from either locally or distantly generated seismic activity must be determined". Based on existing guidance in RG 1.59 and ANS 2.8, the earthquake centering shall be evaluated in a location(s) that produce the worst flooding from a seismically induced dam failure at the nuclear power plant site. In regions where two or more dams are located close together, a single seismic event shall be evaluated to determine if multiple dam failures could occur.

A dam's structural stability shall be demonstrated to survive a local equivalent of the Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE). Given the lack of a probabilistic SSE, as described in 10 CFR 100.23 (d)(1), the deterministic SSEs and OBEs, as defined by the current licensing basis, should be used in this evaluation. These earthquakes may be used for dams that are within the same general tectonic region. For dams that are large distances from the nuclear site, the dam's maximum credible or design earthquake may be used to evaluate for the combined events by using the annual exceedance probability. Per ANS 2.8 (1992), the average annual exceedance for the combined events of 1×10^{-6} is an acceptable goal for selection of flood design bases for the nuclear power reactor plants. Therefore, a cumulative annual exceedance may be determined for the combined flood and earthquake event and compared to the acceptable goal. If the design earthquake and flood cumulative annual exceedance probability is not comparable, additional dam analyses may be required.

Comment [g20]: Additional consideration needs to be given to ongoing review of seismic hazards and the interrelationship with this analysis

The evaluation of the dam's structural stability shall include the concrete and earth sections. The methods for evaluation should be those described by USACE, Bureau of Reclamation (USBR), or Federal Energy Regulatory Commission (FERC). The existing evaluations completed by the dam owner may be used if the review determines that the current standards as prescribed by USACE, USBR, or FERC are used and the required factors of safety per those standards are satisfied. In addition, the annual exceedance probability for maximum credible or design earthquake loading, combined with the hydrologic event annual exceedance probability, shall be 1×10^{-6} or less.

'Sunny-Day' Failure

A sunny-day failure is, as the name implies, a failure that is not induced by a precipitation event. (For the purposes of this paper, a seismically-induced failure is being considered separately.) Sunny-day failures are typically attributed to structural weakness or deficiency in the dam embankment, foundation, and/or abutments. While generally expected not to produce flood discharges and water levels that exceed the hydrologic or seismically-induced failure scenarios, discussed above, it can be associated with the shortest warning times. Some licensees may consider applying sunny-day failure warning times to the seismically-induced failure scenarios; in which case, sunny-day failure may not need to be a consideration at the site. Nevertheless, if a sunny-day failure of an upstream dam is thought to affect the site, information, such as ongoing monitoring (e.g. piezometer wells to monitor seepage), maintenance, and operational procedures, can be provided to demonstrate that a sunny-day failure is not credible.

Comment [g21]: Describe the dam-specific attributes of the maintenance, dam age, risk tolerance of the operating agency. See Information Notice 2012 regarding use of historical failure databases.

Durable maintenance agreement?

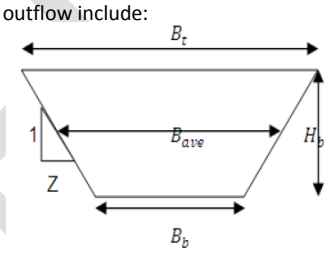
See also ANSI/ANS-2.8-1992 Section 6.3

Breach Formulation

Empirically-Based Methods

Frequently, a refined site-specific analysis is desired to predict dam failure hazard conditions at a nuclear site, accounting for time-progression of the breach and flood attenuation storage along the riverine/floodplain system between the dam and nuclear site. The computer modeling tool frequently used for this analysis is the USACE HEC-RAS Unsteady-Flow model.

HEC-RAS generates a breach hydrograph by calculating discharge values in discrete time-steps as the breach progresses. At each time-step, HEC-RAS calculates a discharge (with a known head) using the weir equation (for an overtopping breach) or orifice equation (for a piping breach). The average discharge is used to estimate the volume released, corresponding drop in pool elevation, and discharge for the subsequent time-step to construct the breach hydrograph. The breach parameters needed for the USACE HEC-RAS Unsteady-Flow model will be the focus of this section. Figure 4 shows the HEC-RAS window view that receives the dam breach parameters. The parameters affecting outflow include:



- Final Bottom Width (B_b)
- Final Bottom Elevation
- Left/Right Side Slope (Z)
- Breach Weir Coefficient (for Overtopping Breaches)
- Full Formulation Time
- Piping/Orifice Coefficient (for Piping Breaches)
- Initial Piping Elevation
- Failure Trigger
  (Water surface elevation, water surface elevation + duration, or user-defined time)
- Starting Water Surface Elevation

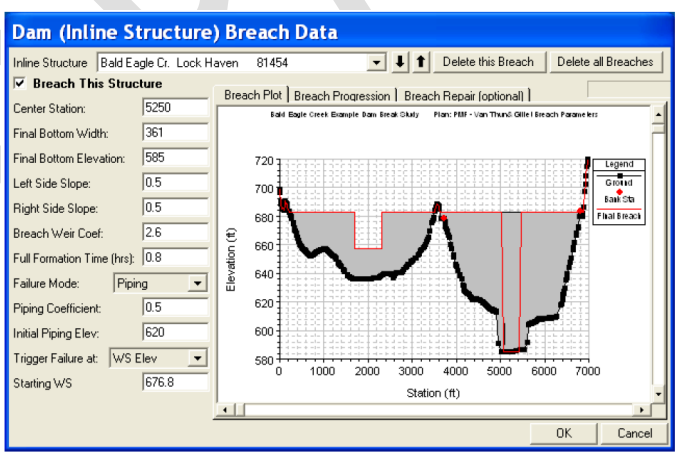


Figure 4 - HEC-RAS Dam Breach Editor

The Bureau of Reclamation (Wahl, 1988) provides additional literature review of breach parameters. Wahl (1998) compiles a list of methods to predict breach parameters. Since estimates of breach parameters vary significantly, Wahl suggested using several methods to establish a range of breach parameters, giving due consideration to the dam's design characteristics.

The USACE (Gee, 2008) provided a review of three (3) regression models for breach parameter development:

- Froehlich (1987, 1995a, 1995b) – Based on 63 earthen, zoned earthen, earthen with a core wall (i.e. clay), and rockfill dams to establish methods to estimate average breach width, side slopes, and failure time.
- MacDonald and Langridge-Monopolis (MacDonald, 1984) – Based on 42 predominately earthfill, earthfill with a clay core, and rockfill dams to establish a 'Breach Formulation Factor' (product of the volume of water released from the dam and the height of the water above the dam).
- Von Thun and Gillette (1990) – Based on 57 dams from both Froehich (1987) and MacDonald and Langridge-Monopolis (1984) papers to estimate side slopes and breach development time.

Gee (2008) indicated that the above parameter estimation methods were applied to five (5) breach situations for comparison and provided the results of these comparisons to two (2) of the five (5) in the 2008 paper. The comparison for the Oros Dam, which failed by an overtopping event in March 1960 in Brazil, is provided in Figure 5. Gee (2008) concluded that "the methods predict a wide range of breach parameters and therefore, a large difference in outflow hydrographs. The MacDonald method routinely produced the largest peak outflows". Gee (2008) also discusses physically-based breach formulation models that use sediment transport functions; this is addressed in the next section.

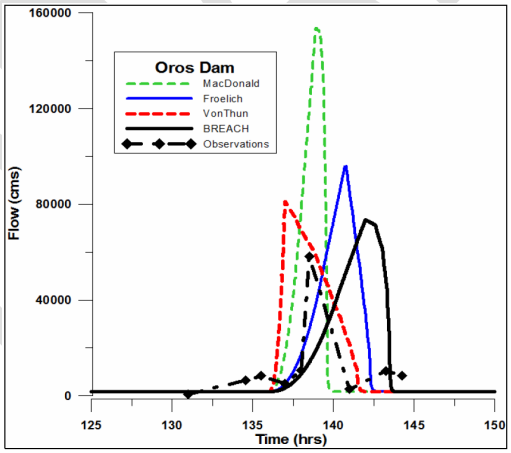


Figure 5 - Breach Hydrographs for Oros Dam (Gee, 2008)

Following a recommendation by Wahl (2008), Xu and Zhang (2009) developed equations to compute breach parameters for earth and rockfill dams. The new equations are based on widely accepted methods developed by Froehlich (1987 and 1995) and empirical data to close the gap between idealized parameters and an analysis of 182 earth and rockfill dam breach events. Of the 182 cases, Xu and Zhang (2009) used the

75 failure cases that had sufficient information to develop regression equations. Xu and Zhang subdivided breaching parameters into two groups, geometric and hydrographic, and included:

- Geometric
  - Breach Depth (H_b)
  - Breach Top Width (B_t)
  - Average Breach Width (B_{ave})
  - Breach Bottom Width (B_b)
  - Breach Side Slope Factor (Z)
- Hydrographic
  - Peak Outflow (Q_p)
  - Failure Time (T_f)

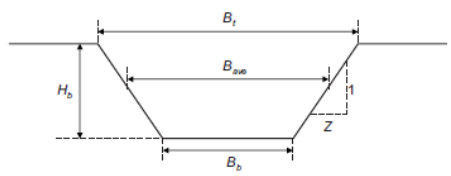


Figure 6 - Geometric Parameters of an Idealized Dam Breach (Xu and Zhang, 2009)

Xu and Zhang (2009) expressed the five key breaching parameters (H_b, B_t, B_{ave}, Q_p, and T_f) in dimensionless forms and five controlling parameters as follows.

Breaching parameters		Control variables			
Breach depth	$Y_1 = H_b / H_d$	Dam height	$X_1 = H_d / H_r$		
Breach top width	$Y_2 = B_t / H_b$	Reservoir shape coefficient	$X_2 = V_w^{1/3} / H_w$		
Average breach width	$Y_3 = B_{ave} / H_b$	Dam type	X_{31}	X_{32}	X_{33}
Peak outflow rate	$Y_4 = Q_p / \sqrt{g V_w^{5/3}}$	with corewalls	1[a](e[b])	0(1)	0(1)
Failure time	$Y_5 = T_f / T_r$	concrete faced	0(1)	1(e)	0(1)
		homogeneous/zoned-fill	0(1)	0(1)	1(e)
		Failure mode	X_{41}	X_{42}	
		overtopping	1(e)	0(1)	
		seepage erosion/piping	0(1)	1(e)	
		Dam erodibility	X_{51}	X_{52}	X_{53}
		high erodibility	1(e)	0(1)	0(1)
		medium erodibility	0(1)	1(e)	0(1)
		low erodibility	0(1)	0(1)	1(e)

Note: [a]Values for additive regression analysis;
[b]Values for multiplicative regression analysis.
H_r = 15 m; T_r = 1 hour.

Figure 7- Summary of the Five Breaching and Control Parameters (Xu and Zhang, 2009)

A multi-variable regression analysis was conducted to generate the following equations for breach parameters:

Where:

- Variables use metric units (meters for length/width/height and cubic meters for volume).
- Time variables are in units of hours.
- H_r = 15 meters.
- T_r = 1 hour.
- $B_2 = b_3 + b_4 + b_5$ for Equation 14.
- $B_3 = b_3 + b_4 + b_5$ for Equation 15.
- $B_5 = b_3 + b_4 + b_5$ for Equation 17.
- b_3 represents the type of dam, b_4 represents the failure mechanism of breach, and b_5 and C_{11} represents erodibility for the respective equations.
- See Table 1.

Table 1 - Constants for Use in Breach Parameter Equations (Xu and Zhang, 2009)

Variable	B_2 (Eq. 14)	B_3 (Eq. 15)	B_5 (Eq. 17)
Dam Description (b_3)			
Corewalls	0.061	-0.41	-0.327
Concrete Face	0.088	0.026	-0.674
Homogeneous/Core Fill	-0.089	-0.226	-0.189
Failure Mode (b_4)			
Overtopping	0.299	0.149	-0.579
Seepage/Piping	-0.239	-0.389	-0.611
Erodibility (b_5)			
High	0.411	0.291	-1.205
Medium	-0.062	-0.14	-0.564
Low	-0.289	-0.391	0.579
Erodibility (C_{11} in Eq. 13)			
High	1.04		
Medium	0.947		
Low	0.804		

Xu and Zhang (2009) also provide the results of two case studies, the Banqiao and Teton dam failures. Refer to Table 2 and Table 3.

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Additional Consideration for Concrete Dams

In general, the current approach to concrete dams is instantaneous failure. The analysis does not necessarily need to include failure of the entire dam. For example, for a dam with large gates on the top, it may be reasonable to analyze a failure mode where only the gates fail, but that the concrete portion of the dam beneath and adjacent to the gates remains intact.

Physically-Based Methods

In 2004, the Centre for Energy Advancement through Technological Innovation (CEATI) formed a Dam Safety Interest Group (DSIG) to investigate the available physically-based numerical models to simulate embankment erosion and breach development. The DSIG group comprised members from the USACE, USBR, USDA, BC Hydro, Elforsk (Scandinavian Utility), and EDF (French Utility). The objective was to compare the available modeling tools and recommend models for further development and use in prediction of embankment breach formulation. The review and validation by the CEATI DSIG Project included:

- International review of breach models;
- Selection of 3 most promising for closer evaluation;
- Review and collation of field and laboratory data;
- Evaluation of model performance against seven selected data sets;
    - Two from USDA Stillwater;
    - Three from the European IMPACT project; and
    - Two from actual dam failures (Oros, Banquio).

The DSIG Project concluded that:

- The HR BREACH and SIMBA/WinDAM best representative; and
- HR BREACH offers zoned cross-section analysis.

Table 4 provides a more comprehensive comparison of the findings.

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Table 2 - Comparison of Physically-Based/Erosion Process Models

	HR-BREACH	SIMBA / WinDAM	FIREBIRD	NWS-BREACH
Erosion Process Models	Good	Good	**Fair**	**Limited**
Surface protection	Vegetation (CIRIA) and riprap	Vegetation, riprap in WinDAM	**Limited**	Yes
Headcut erosion	Good	Best	**No**	**No**
Stress-based	—	Yes	—	—
Energy-based	Yes	Yes (in WinDAM)	—	—
Surface erosion	Yes	**No**	Yes	Yes
Mass-wasting / soil-wasting	Stress-based bank failures and arch failure	Bank failures implicit	**Some**	**Some**
Effects of Submergence	Yes	Yes (in WinDAM)	**No**	Yes
Piping progression	Yes	In development	**Some**	Yes
Data Input Guidance	Good	Good	**Limited**	**Limited**
Ease of Use	Good	Good	**Difficult**	**Difficult**
Computational Efficiency	Good	Good	**Fair**	Good
Documentation	Excellent	Excellent	**Limited**	Good
Organizational Support for Continued Development	Good	Good	**Weak**	**None**
Embankment Geometry Options	Simple Zoning	Homogeneous, (Zoned in future)	Simple Zoning	Primitive Zoning

Uncertainty in Breach Formulation

In general, uncertainty in formulating a dam failure should be evaluated by applying multiple methods, applicable to the dam in question, and evaluating sensitivity to reasonable variations in input parameters. Xu and Zhang (2009) developed a comparison in empirical prediction equations using the case studies in their research, which will produce bias towards the Xu and Zhang results. (See Table 5.) Nevertheless, the Xu and Zhang method appears to offer the least variability and seems to accommodate a wider range of situations.

Table 3 - Comparison of Different Parameter Prediction Equations based on Case Studies in Xu and Zhang (2009)

	Best prediction models in this paper			Best-simplified prediction models in this paper			Bureau of Reclamation (1982, 1988)			Froehlich (1995a,b)		
Parameter	Number of cases[a]	Mean	SD	Number of cases[a]	Mean	SD	Number of cases[a]	Mean	SD	Number of cases[a]	Mean	SD
H_b	62	1.01	0.08	66	1.01	0.08	—	—	—	—	—	—
B_t	52	1.03	0.32	59	1.03	0.32	—	—	—	—	—	—
B_{ave}	43	1.02	0.32	52	1.03	0.33	51	1.31	0.94	51	1.07	0.43
Q_p	33	1.01	0.34	38	1.03	0.39	36	0.95	0.80	36	1.30	0.84
T_f	27	1.02	0.43	28	1.02	0.44	27	3.08	4.00	27	2.30	2.05

[a]The number of cases after using the objective outlier-exclusion algorithm (Rousseeuw 1998) at the 95% probability level.

Breach Hydrograph Routing

1-Dimensional

Flood hydrograph routing in a 1-dimensional model is a procedure to determine the time and magnitude of flow passing though a hydrologic system, such as reservoirs, ponds, channels, floodplains, etc. Flood routing accounts for changes in the time distribution of flood flows caused by storage and attenuation. The effect of storage is to re-distribute the hydrograph by shifting the centroid of the inflow hydrograph by the time of re-distribution to form the outflow hydrograph. The time of re-distribution occurs for level pool or reservoir routing situations. For very long channels, the entire flood wave travels a considerable distance and the centroid of its hydrograph may then be shifted by a time period longer than the time of re-distribution; called time of translation. The total shift in centroid can be called the time of flood movement, equal to the combined effect of the time of re-distribution and time of translation. See Figure 8.

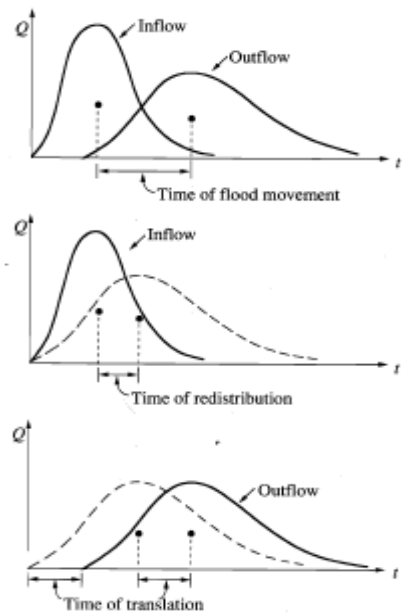

Figure 8 – Hydrograph Attenuation and Redistribution

The process for reservoir (level pool) routing can be expressed using the Continuity Equation (below). The inflow hydrograph, *I(t)*, is typically known. The outflow hydrograph, *Q(t),* can be solved with another relationship, called a storage function, to relate *S*, *I*, and *Q*.

Equation 6 - Continuity

—

Other routing computations, including channel/floodplain routing, can vary in complexity; this paper will focus on the two typically used for dam breach routing. Both are based on the St. Venant equation, derived from the combination of the continuity and momentum equations, as illustrated below. As indicated in Equation 7, the St. Venant equation can be applied in 1-dimensional models for:

- **Kinematic (Simplified) Wave Routing** – The kinematic wave routing is based on a finite difference estimation of the continuity equation and simplification of the momentum equation (assume $S_f = S_o$). As indicated in Equation 7, the solution assumes steady-state and uniform flow conditions. The kinematic wave routing method is used in the USACE HEC-HMS model.
- **Dynamic (Time-Dependent or Unsteady) Wave Routing** – The dynamic wave method is a more accurate routing procedure that solves the entire St. Venant equation (Equation 7) and considers changes in flow rates with respect to time, a factor that can be significant with a dam breach wave. The dynamic wave routing method is used in the USACE HEC-RAS (unsteady-flow) model, MIKE 21, the NWS FLDWAV model, and others. Developing a model using dynamic wave routing techniques involves much greater effort than the kinematic wave solution but produces more accurate results. After the initial setup, a dynamic wave model frequently requires refinements to cross-section spacing and computational time increments to reach and maintain model stability.

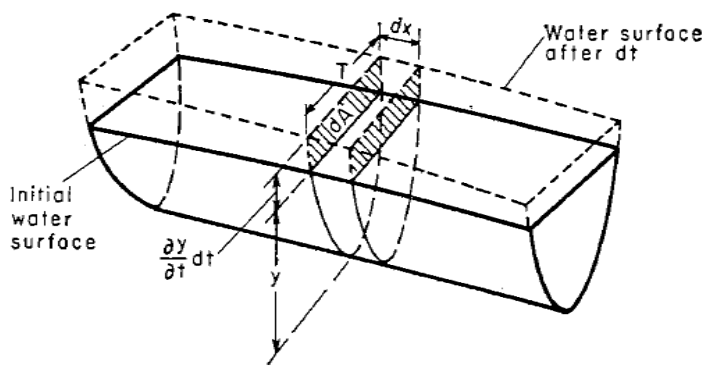

Figure 9 – Definition Sketch for St. Venant Equation

Equation 7 - St. Venant Equation

$$\underbrace{\frac{\partial Q}{\partial t}}_{\text{Unsteady Varied}} \quad \underbrace{\frac{\partial Q}{\partial x}}_{\text{Steady Varied}} \quad \underbrace{\frac{\partial Q}{\partial y}}_{\text{Steady Uniform}}$$

Kinematic Wave Solution

Dynamic Wave Solution

2-Dimensional

In some cases, flow pattern complexities, unusual dam failure configurations, and/or a desire for increased accuracy warrants the use of Two Dimensional (2D) (finite-element or finite-difference) hydrodynamic modeling to simulate the affects of dam failure. 2D models have the added advantage of producing velocity vectors (direction and magnitude) at the site to better assess hydrodynamic and debris loading conditions at the site due to dam failure. Some 2D models use finite-element solutions of continuity and momentum functions based on a triangular mesh, representing the surface terrain, developed from a series of points/nodes with X, Y, Z attributes. Other 2D models use finite-difference solution methods based on a surface terrain represented by grid elements. Some 2D models can be used to generate and route breach hydrographs; others can only perform the hydrodynamic routing of a user defined breach hydrograph. Example models include:

- HEC-RAS 4.2 (currently being beta-tested but is expected to include a 2D component)
- RiverFLO-2D
- FLO-2D
- River-2D
- MIKE-21
- SRH-2-D Model (The Bureau of Reclamations)

D. Pertinent References

AlQaser, G., and Ruff, J.F., 1993. Progressive failure of an overtopped embankment. In *Hydraulic Engineering*, Proceedings of the 1993 ASCE Hydraulic Specialty Conference, San Francisco, California, July 25-30, 1993.

American Nuclear Society (ANS). 1992. *American National Standard for Determining Design Basis Flooding at Power Reactor Sites*. Prepared by the American Nuclear Society Standards Committee Working Group ANS-2.8, La Grange Park, Illinois.

Andrews, D.P., Coleman, S.E., Webby, M.G., and Melville, B.W., 1999. Noncohesive embankment failure due to overtopping flow. Proceedings, 28th Congress of the International Association for Hydraulic Research, Graz, Austria.

Bechteler W., Broich K. (1993), Computational Analysis of the Dam Erosion Problem, Proceedings of the International Conference on Hydroscience and Engineering, Washington DC, Junho.

Chow V.T. 1959. *Open-Channel Hydraulics*. McGraw-Hill Book Company, New York.

Chow V.T., D.R. Maidment, and L.W. Mays. 1988. "Applied Hydrology." McGraw-Hill Book Company, New York.

Coleman, S.E., R.C. Jack, and B.W. Melville, 1997. Overtopping Breaching of Noncohesive Embankment Dams. 27th IAHR Congress, San Francisco, California, August 10-15, 1997. p. 42-47.

DRAFT

Coleman, Stephen E., Darryl P. Andrews, and M. Grant Webby, 2002. "Overtopping Breaching of Noncohesive Homogeneous Embankments," *Journal of Hydraulic Engineering*, vol. 128, no. 9, Sept. 2002, p. 829-838.

Coleman, Stephen E., Darryl P. Andrews, and M. Grant Webby, 2004. Closure to "Overtopping Breaching of Noncohesive Homogeneous Embankments," *Journal of Hydraulic Engineering*, vol. 130, no. 4, April 2004, p. 374-376.

Colorado Department of Natural Resources, Office of the State Engineer, Division of Water Resources, Dam Safety Branch. 2010. "Guidelines for Dam Breach Analysis", State of Colorado, Department of Natural Resources, February 10.

Cristofano E. A. (1965), Method of Computing Erosion Rate for Failure of Earthfill Dams, U. S. Bureau of Reclamation, Denver.

Dewey, Robert L., and David R. Gillette, 1993, "Prediction of Embankment Dam Breaching for Hazard Assessment," *Proceedings*, ASCE Specialty Conference on Geotechnical Practice in Dam Rehabilitation, Raleigh, North Carolina, April 25-28, 1993.

Dewey, Robert L., and Ronald A. Oaks, 1990, *The Determination of Failure of an Embankment Dam During Overtopping*, draft Technical Memorandum No. MISC-620-1, Bureau o f Reclamation, Denver, Colorado, May 1989, revised April 1990.

Evans, Steven G., 1986, "The Maximum Discharge of Outburst Floods Caused by the Breaching of Man-Made and Natural Dams," Canadian Geotechnical Journal, vol. 23, August 1986.

Federal Emergency Management Agency. 2010. "Numerical Models Meeting the Minimum Requirement of National Flood Insurance Program." Available at http://www.fema.gov/plan/prevent/fhm/en_coast.shtm. Accessed December 20, 2010.

Federal Energy Regulatory Commission, 1987, Engineering Guidelines for the Evaluation of Hydropower Projects, FERC 0119-1, Office of Hydropower Licensing, July 1987, 9 p.

Federal Energy Regulatory Commission. 2001. *Engineering Guidelines for the Evaluation of Hydropower Projects*. Chapter 8 – "Determination of the Probable Maximum Flood." Washington, D.C.

Franca, M.J., and Almeida, A.B., 2002. Experimental tests on rockfill dam breaching process. International Symposium on Hydraulic and Hydrological Aspects of Reliability and Safety Assessment of Hydraulic Structures, St. Petersburg, Russia. May 29-June 2 2002.

Franca, M.J., and Almeida, A.B., 2004. A computational model of rockfill dam breaching caused by overtopping (RoDaB). *Journal of Hydraulic Research*, Vol. 42, No. 2, pp. 197-206.

Froehlich, 2008

Froehlich, D.C. 1995a. Embankment dam breach parameters revisited. Proceedings of the 1995 ASCE Conference on Water Resources Engineering, San Antonio, Texas. August. p. 887-891.

Froehlich, D.C. 1995b. Peak Outflow from Breached Embankment Dam. Journal of Water Resources Planning and Management, vol. 121, no. 1, p. 90-97.

Froehlich, David C., 1995b, "Embankment Dam Breach Parameters Revisited," Water Resources Engineering, Proceedings of the 1995 ASCE Conference on Water Resources Engineering, San Antonio, Texas, August 14-18, 1995, p. 887-891.

Froehlich, David C., and Tufail, M., 2004. Evaluation and use of embankment dam breach parameters and their uncertainties. Annual Conference of Association of State Dam Safety Officials, September, Phoenix, Arizona.

Gee, D. Michael (2008), "Comparison of Dam Breach Parameter Estimators", Corps of Engineers Hydrologic Engineering Center, Davis, CA.

Gerodetti, M., 1981, "Model Studies of an Overtopped Rockfill Dam," *International Water Power & Dam Construction*, September 1981, p. 25-31.

Hartung, F., and H. Scheuerlein, 1970, "Design of Overflow Rockfill Dams," in *Proceedings*, International Commission on Large Dams, Tenth International Congress on Large Dams,

Hunt, S., Hanson, G.J., Temple, D.M., Kadavy, K.C. 2005b. Embankment Overtopping and RCC Stepped Spillway Research. In: American Society of Agricultural Engineers Annual International Meeting, July 17-20, 2005, Tampa, Florida. Paper No. 05-2204. CD-ROM.

Knauss, J., 1979, "Computation of Maximum Discharge at Overflow Rockfill Dams," *Proceedings*, International Commission on Large Dams, Thirteenth International Congress on Large Dams, Q.50, R.9, New Delhi, India, 1979, p. 143-160.

Ko, H.Y., Dunn, R.J., and Hollingsworth, T., 1985. Study of embankment performance during overtopping-prototype modeling and dimensional verification. U.S. Army Corps of Engineers, Waterways Experiment Stations, Vicksburg, Mississippi.

Ko, H.Y., Dunn, R.J., and Simantob, E., 1984. Study of embankment performance during overtopping and throughflow. U.S. Army Corps of Engineers, Waterways Experiment Stations, Vicksburg, Mississippi.

Lecointe, G., 1998. "Breaching mechanisms of embankments an overview of previous studies and the models produced." CADAM Meeting, Munich, Germany. 8-9 October 1998.

Lou W. C. (1981), Mathematical Modeling of Earth Dam Breaches – Dissertação de Doutoramento, Colorado State University – Fort Collins (não publicado).

Loukola E. e Huokuna M. (1998), A Numerical Erosion Model for Embankment Dams Failure and It's Use for Risk Assessment, Proceedings of the 2nd CADAM Workshop, Munich. Outubro.

M.W. Pierce, C.I. Thornton, and S.R. Abt. 2010. "Predicting Peak Outflow from Breached Embankment Dams", Colorado State University. June 2010

MacDonald, T. C., and Langridge-Monopolis, J. (1984), "Breaching Characteristics of Dam Failures," ASCE J. Hydraulic Engineering, 110(5), 567-586.

Martins R. (1981), Hydraulics of Overflow Rockfill Dams, LNEC – Me 559, Lisboa.

Martins R. (1996), Design Criteria for Rockfill Structures Subjected to Flow, LNEC – Me 807, Lisboa.

Mohamed A. A., Samuels P. G. e Morris M. W. (1998), A New Methodology to Model the Breaching of Non-Cohesive Homogeneous Embankments, Proceedings of the 4th CADAM Workshop, Saragoça, Novembro.

NUREG CR/7046 – under contract by Pacific Northwest National Laboratory, Richland Washington

NUREG/CR-7046, PNNL-20091, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America." ML11321A195, November 2011.

DRAFT

NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition – Site Characteristics and Site Parameters (Chapter 2)," ML070400364, March 2007.

Ponce V. M. e Tsivoglou A. J. (1981), Modeling Gradual Dam Breaches, Journal of Hydraulics Division, Vol. 107, N. HY7, 829-838.

Powledge G. R., Ralston D. C., Miller P., Chen Y. H., Clopper P. E. e Temple D. M. (1989), Mechanics of Overflow Erosion on Embankments. II: Hydraulic and Design Considerations, Journal of Hydraulic Engineering Vol. 115, Nº 8 Agosto. - Quintela A. C. (1981), Hidráulica, Fundação Calouste Gulbenkian, Lisboa.

Prediction of Embankment Dam Breach Parameters, DSO-98-004

Q.36, R.35, Montreal, Canada, June 1-5, 1970, p. 587-598.

Reg Guide 1.1.27, INSPECTION OF WATER-CONTROL STRUCTURES ASSOCIATED WITH NUCLEAR POWER PLANTS.

Reg Guide 1.102 Flood Protection for Nuclear Power Plants

Reg Guide 1.59 – Design Basis Floods for Nuclear Power Plants

SECY 11-0124, "Recommended Actions To Be Taken Without Delay from the Near-Term Task Force Report," ML11245A158, September 9, 2011.

SECY 11-0137, "Prioritization of Recommended Actions to Be Taken in Response to Fukushima Lessons Learned," ML11272A111, October 3, 2011.

SRM SECY 11-0124, "Recommended Actions To Be Taken Without Delay from the Near-Term Task Force Report," ML112911571, October 18, 2011.

SRM SECY 11-0137, "Prioritization of Recommended Actions to Be Taken in Response to Fukushima Lessons Learned," ML113490055, dated December 15, 2011.

Stephenson D. (1979), Rockfill in Hydraulic Engineering, Elsevier Scientific Publishing Company, Amesterdão.

U.S. Army Corps of Engineers (USACE), *River Hydraulics*, Engineer Manual (EM) 1110-2-1416

U.S. Army Corps of Engineers (USACE), *Standard Project Flood Determinations*, Engineer Manual (EM) 1110-2-1411

U.S. Army Corps of Engineers (USACE). 1991. "Inflow design floods for dams and reservoirs." Engineer Regulation 1110-8-2(FR), Washington, D.C.

U.S. Army Corps of Engineers (USACE). 1997. *Hydrologic Engineering Requirements for Reservoirs*. Engineer Manual 1110-2-1420, Washington, D.C.

U.S. Army Corps of Engineers (USACE). 2008a. *HEC-RAS River Analysis System User's Manual*. Version 4.0. U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, California. Available at http://www.hec.usace.army.mil/software/hec-ras/documents/HECRAS_4.0_Users_Manual.pdf. Accessed June 10, 2009.

U.S. Army Corps of Engineers (USACE). 2008b. "Hydrologic Modeling System HEC-HMS User's Manual. Version 3.3." U.S. Army Corps of Engineers Hydrologic Engineering Center, Davis, California. Available at

DRAFT

http://www.hec.usace.army.mil/software/hechms/documentation/HEC-HMS_Users_Manual_3.3.pdf. Accessed June 9, 2009.

U.S. Army Corps of Engineers (USACE). 2008c. *Inflow Flood Hydrographs*. USACE Dam Safety Program Portfolio Risk Assessment Draft Report, Washington D.C.

U.S. Army Corps of Engineers (USACE). 2009b. "Hydrologic Modeling System (HEC-HMS)." Available at http://www.hec.usace.army.mil/software/hec-hms/. Accessed June 9, 2009, 2009c.

U.S. Army Corps of Engineers (USACE). 2009c "River Analysis System (HEC-RAS)." Available at http://www.hec.usace.army.mil/software/hec-ras/. Accessed June 10, 2009, 2009d.

U.S. Army Corps of Engineers (USACE). 2010. "Hydrologic Modeling System (HEC-HMS) Validation Guide, Version 3.5." Available at http://www.hec.usace.army.mil/software/hec-hms/. Accessed December 20, 2010, 2010.

U.S. Army Corps of Engineers (USACE). 1991. *Inflow Design Floods for Dams and Reservoirs*. Engineer Regulation 1110-8-2(FR), Washington, D.C.

U.S. Bureau of Reclamation (USBR). 1982. "Guidelines for defining inundated areas downstream from Bureau of Reclamation dams." *Reclamation Planning Instruction No. 82-11*, June 15.

U.S. Department of Agriculture (USDA). 1985. Soil Conservation Service. Technical Release No. 66. *Simplified Dam Breach Routing Procedure*. September 30.

U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS), Technical Release 60 (TR-60), "Earth Dams and Reservoirs", July 2005

U.S. Department of Interior, Bureau of Reclamation (Reclamation). 1987. *Design of Small Dams*. Third Edition. A Water Resources Technical Publication, Washington, D.C.

U.S. Department of Interior, Bureau of Reclamation (Reclamation). 2010. *Best Practices in Dam Safety Risk Analysis, Version 2.1*. Denver, Colorado.

U.S. Department of Interior, Bureau of Reclamation (Reclamation). 2003. *Guidelines for Achieving Public Protection in Dam Safety Decision-Making*. Denver, Colorado.

U.S. Department of Interior, Bureau of Reclamation (Reclamation). 1977. *Design of Arch Dams*. A Water Resources Technical Publication, Denver, Colorado.

U.S. Department of Interior, Bureau of Reclamation (Reclamation). 1976. *Design of Gravity Dams*. A Water Resources Technical Publication, Denver, Colorado.

U.S. Nuclear Regulatory Commission (NRC). 1976. *Flood Protection for Nuclear Power Plants*. Regulatory Guide 1.102, Rev. 1, Washington, D.C.

U.S. Nuclear Regulatory Commission (NRC). 1977. *Design Basis Flood for Nuclear Power Plants*. Regulatory Guide 1.59, Rev. 2, Washington, D.C.

US Nuclear Regulatory Commission. 2011. *Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-term Task Force Review of Insights from the Fukushima Dai-ichi Accident*, ML111861807, July 12.

Vaskinn, K.A., Løvoll, A., and Höeg, K., undated. WP2.1 BREACH FORMATION- LARGE SCALE EMBANKMENT FAILURE.

Von Thun, J. L., and Gillette, D. R. (1990), "Guidance on Breach Parameters," Internal Memorandum, U.S. Dept. of the Interior, Bureau of Reclamation, Denver, CO.

Von Thun, J.L., and Gillette, D.R., 1990. *Guidance on Breach Parameters.* Unpublished internal document, Bureau of Reclamation, Denver, Colorado, March 13, 1990, 17 p.

Wahl T. L. (1997), Predicting Embankment Dam Breach Parameters – A Needs Assessment, Proceedings of Energy and Water: Sustainable Development, São Francisco, Agosto.

Wahl T. L. (2001), The Uncertainty of Embankment Dam Breach Parameter Predictions Based on Dam Failure Case Studies, Proceedings of USDA/FEMA Workshop on Issues - Resolutions and Research Needs Related to Dam Failure Analysis, Oklahoma City, Junho.

Wahl T.L. 1998. Prediction of Embankment Dam Breach Parameters: A Literature Review and Needs Assessment. DSO-98-004, Dam Safety Research Report, Water Resources Research Laboratory, U.S. Department of the Interior, Bureau of Reclamation Dam Safety Office, Washington, D.C.

Wahl, 2010

Wahl, Tony L. (1988), "Prediction of Embankment Dam Breach Parameters – A Literature Review and Needs Assessment," DSO-98-004, Dam Safety Research Report, U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office, July 1998. http://www.usbr.gov/pmts/hydraulics_lab/twahl/breach/breach_links.html

Wahl, Tony L., 1998, *Prediction of Embankment Dam Breach Parameters: A Literature Review and Needs Assessment*, Dam Safety Research Report DSO98-004, U.S. Dept. of the Interior, Bureau of Reclamation, Denver, Colorado, July 1998.

Wahl, Tony L., 2004. "Uncertainty of predictions of embankment dam breach parameters". *Journal of Hydraulic Engineering*, Vol. 130, No. 5, pp. 389-397.

Wahl, Tony L., et al. (2008), "Development of Next-Generation Embankment Dam Breach Models," United States Society on Dams, 28th Annual USSD Conference, Portland, OR, April 28-May 2, 2008, pp. 767-779.

Xu, Y. and Zhang, L. M. (2009), "Breaching Parameters for Earth and Rockfill Dams," ASCE J. Geotechnical and Geoenvironmental Engineering, 135(12), December 1, 1957-1970.

Y. Xu and L.M. Zang, "Breaching Parameters for Earth and Rockfill Dams", Journal of Geotechnical and Geoenvironmental Engineering, December 2009.

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