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Subject: Dam Failure DRAFT 07-08-12.docx
Date: Tuesday, July 10, 2012 5:35:45 PM
Attachments: Dam Failure DRAFT 07-08-12.docx

Ed, Chris,

I have attached a preliminary version of the first sections of our dam failure white paper for your review prior to our meeting on Wednesday afternoon. This is a work in progress that illustrates our approach, items to be addressed and level of detail. Your feedback on where this is heading would be beneficial.

Thanks,

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POST-FUKUSHIMA NEAR-TERM TASK FORCE RECOMMENDATION 2.1
Evaluation of Dam Failures

Contents

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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

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 addresses two approaches to conducting flood evaluations – deterministic and probabilistic. Deterministic methods use empirical, mathematical, and/or physical relationships to

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simulate flooding for a given/specified event or set of events. Typically, the specified event or set of events is established by defining a theoretical maximum event (e.g. Probable Maximum Precipitation (PMP), Probable Maximum Flood (PMF), Probable Maximum Hurricane (PMH), etc.) given physically limiting parameters (e.g. maximum precipitable water in the atmosphere).

Probabilistic methods are used to establish a relationship between flood magnitude and exceedance probability (typically expressed as percent chance of being equaled or exceeded in any given year (p) or annual recurrence interval (1/p)). Probabilistic methods typically require the use probability distribution models, known to be representative of specified random, extreme flood-causing events (i.e. extreme rainfall, river flow, storm surge, etc.). Probability models are typically 'fitted' to historical flood/precipitation data and, given the limited period of observed flood/precipitation records, subject to significant uncertainty at low exceedance probabilities. Example probability distributions frequently used in flooding evaluations include Log-Pearson Type III and Extreme Value (Types I and II).

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. Besides high uncertainty at low annual exceedance probabilities, a challenge with using probabilistic methods in flood estimation at nuclear power plants is using a flood-frequency function within the context of Probability Risk Assessment (PRA) models, which estimates annual core damage probability to 10^{-6}. Extrapolating flood-frequency functions to, or beyond, a 10^{-6} annual exceedance probability usually results in exceeding physical limits of flood-causing processes (theoretically captured as the PMP, PMF, PMH, etc.). Further research and development is needed to apply probabilistic methods to flood estimation at nuclear power plants. Such research may include other techniques, such as Monte-Carlo simulations, to estimate frequency of extreme floods. Therefore, the methods in NUREG/CR-7046 focus on the use of deterministic methods.

- **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, 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 that may be located at or above SSCs important to safety should also be evaluated. 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 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 with appropriate jurisdiction for dams may be used. Dam breach/failure scenarios should include coincidental failure with the peak PMF and domino-type or cascading dam failures. 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. Problem Statement

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 50.54(f) letter. The following is a summary of guidance provided in NUREG/CR-7046, Sections 3.4 and 3.9 and Appendix H.2, related to dam failure considerations:

- **Hydrologic 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 Failure:** Per Appendix H.2 of NUREG/CR-7046, the following seismic/precipitation combinations will be considered:
  1. Shut-down earthquake and 25-year precipitation.
  2. Operational earthquake and ½ PMP or 500-year precipitation.
  3. Cascading failures of dams in series should also be considered. As part of the HHA approach, the analysis could assume that all dams fail, even under the lesser (operational) seismic event, and apply the ½ PMP.

- **Sunny Day 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.
- **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.

Evaluating dam failure should include the following considerations:

- Breach Mechanism
    - Piping (earthen, rockfill)
    - Overtopping (earthen, rockfill)
    - Seismic liquefaction (earthen, rockfill)
    - Seismic crack and fail (concrete)
    - Overturning (concrete gravity)
    - Sliding (concrete gravity)
    - Instantaneous disappearance (arch)
- Breach Geometry
    - Breach depth
    - Breach width
    - Breach side slope factor
- Failure Outflow Hydrograph
    - Breach initiation time
    - Breach formation time
    - Failure progression (sine wave, linear, etc)
    - Peak flow time and rate
- Breach elevation
    - Elevation of initial failure within the dam structure
- Initial Reservoir Elevation
    - Full pond
    - Full pond with PMP

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C. Approach

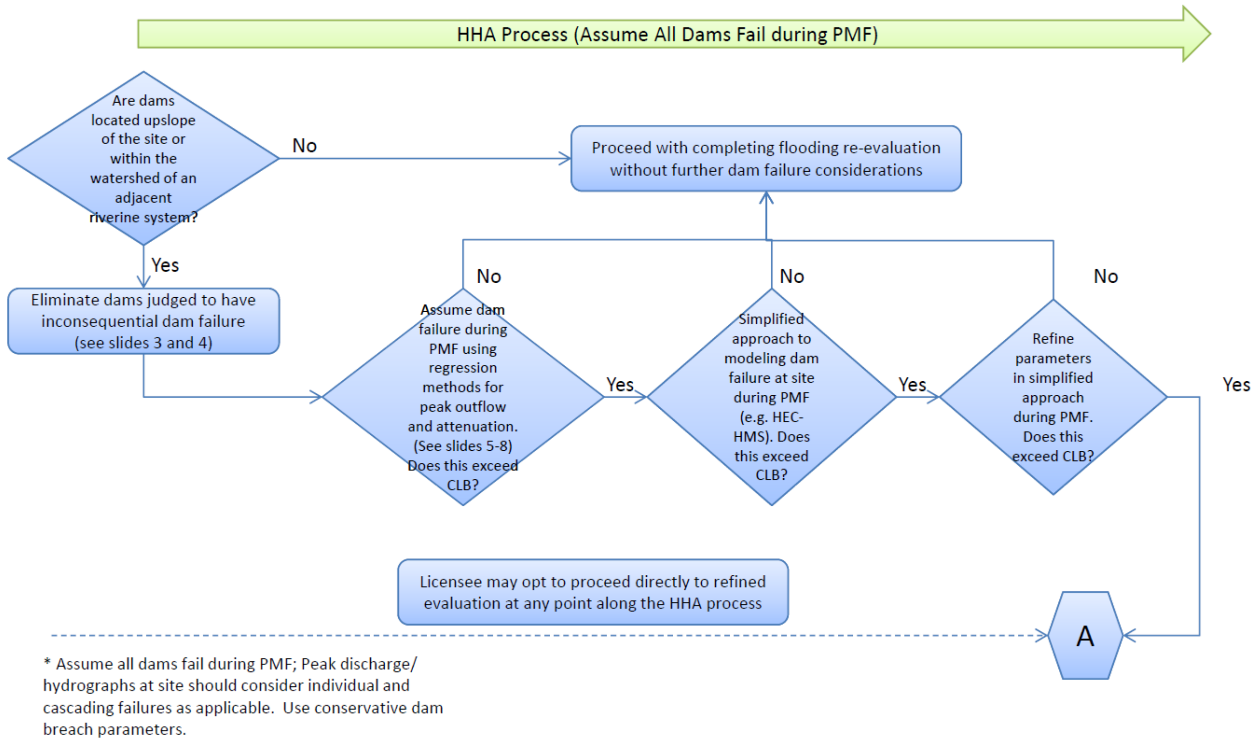

Figure 1 - Dam Failure Process/Decision Flow Chart

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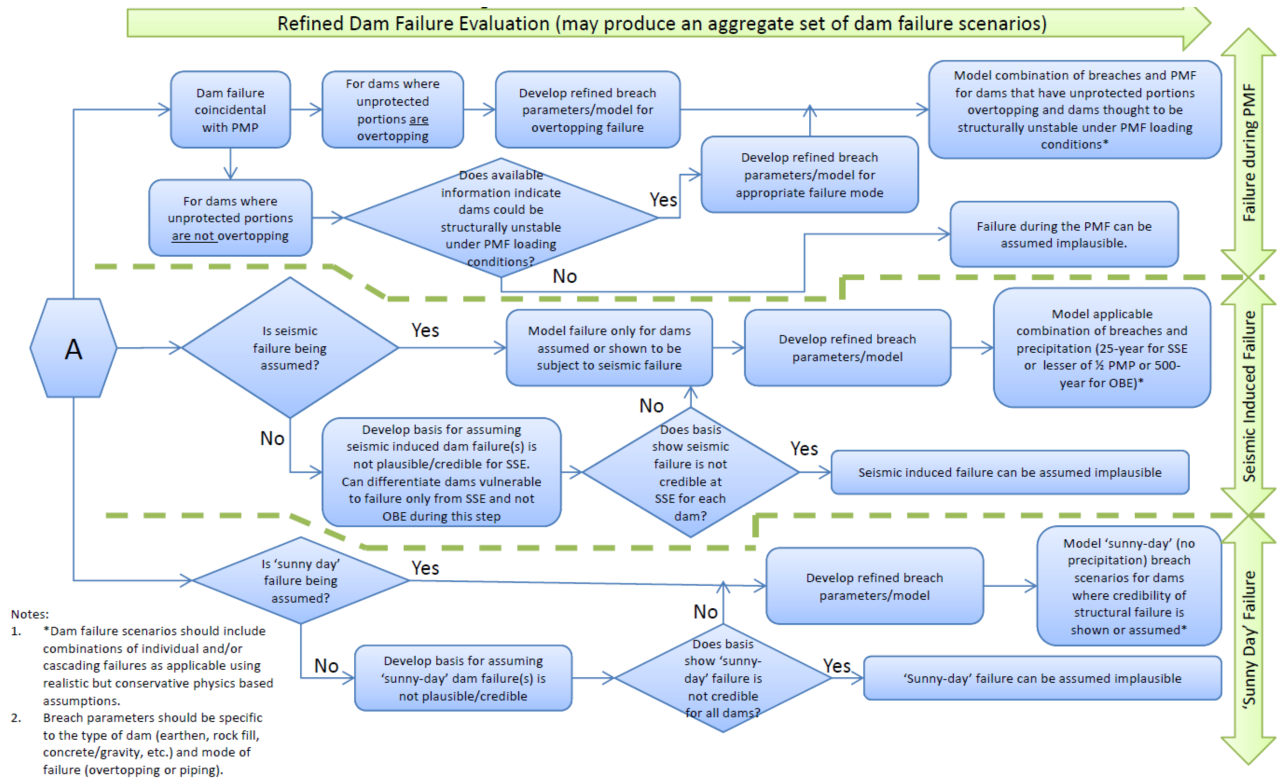

C.1 Hierarchical Hazard Assessment (HHA) Approach for Dam Failure

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.

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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:

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),

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,

Equation 5

Equation 5 is plotted on Figure 1 for a range of allowable dam breach peak flow rates at the site, from 1,000 to 200,000 cfs. Figure 1 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 1 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 1, 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.

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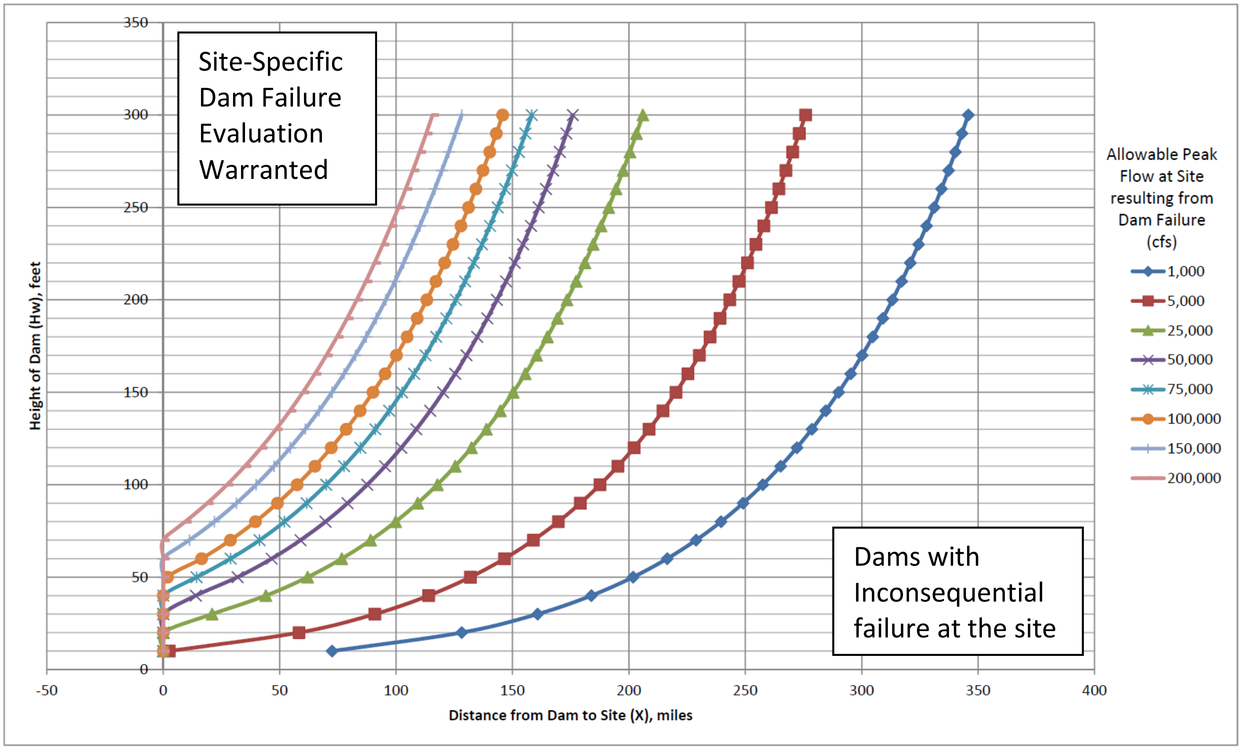

Figure 2 – Distance/Height of Dam Plot

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)

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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 $B_r = 9.5K_o(V_sH)^{0.25}$

C = 23.4 x 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), use H/120 or minimum of 10 minutes or $T_f = 0.59(V_s^{0.47})(H^{0.91})$

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)

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B_r = Breach factor (acre)

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)

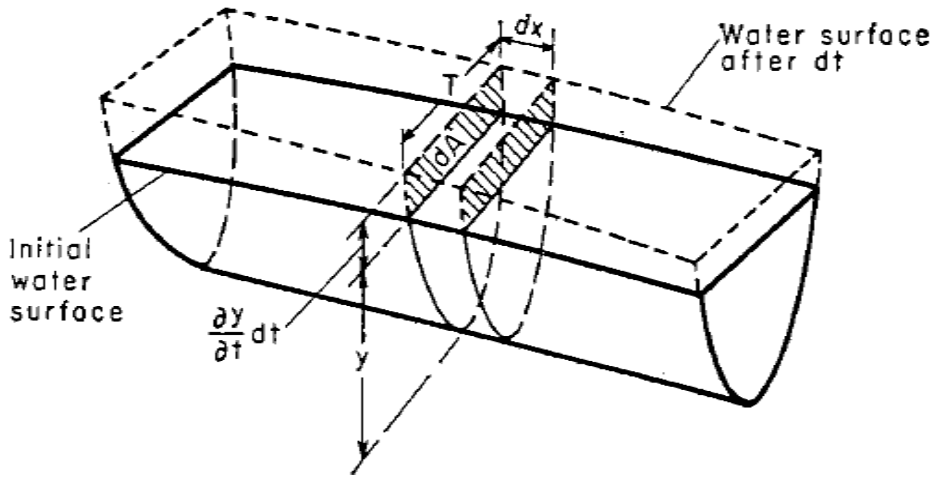
Q_r = Peak discharge corresponding to distance X (cfs)

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

Use of Rainfall-Runoff Model to Evaluated 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, it's 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. Channel/floodplain routing computations are based on the St. Venant equation, derived from the application of continuity and momentum principles, as illustrated below.



Equation 6 - St. Venant Equation

Unsteady Varied | Steady Varied | Steady Uniform

Kinematic Wave Solution

Dynamic Wave Solution

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 2, 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

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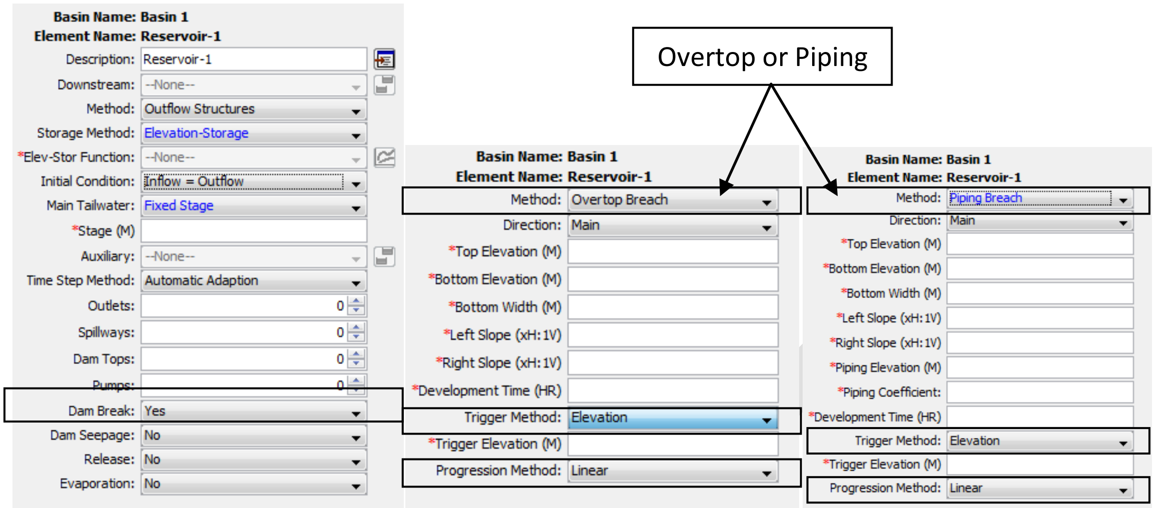

Figure 3- Dam Breach Menu Options in HEC-HMS

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 Dam Failure Evaluation

Breach Scenarios

Individual and Cascading Failures

Summarize approach to considering individual and cascading failures in NUREG/CR-7046.

Overtopping Failure

Discuss overtopping failure evaluation approach.

Seismically-Induced Failure

Discuss seismically-induced failure evaluation approach.

Embankment Dams

Seismic failure comes from three modes:

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1. Instability/deformation lowers the top of the dam below the water level. Usually a result of liquefiable material in the dam or the foundation.

2. Settlement/displacement results in cracks in the dam extending below the reservoir level leading to a piping failures.

3. Settlement/displacement where the embankment abuts a concrete structure (spillway, etc) moves the embankment material away from the concrete.

In general a dam that was constructed with well compacted material without liquefiable soil in the embankment or foundation will probably not deform enough to be a problem unless the freeboard is unusually low. Particularly if it has filters up to and above the reservoir level.

Also it was mentioned that as a general rule of thumb that this type of failure is unlike if acceleration is less than 0.1g.

Concrete Dams

It was mentioned that "slab and butress" dams (reinforced concrete dams) are highly susceptible to seismic failure. So.. for that type of dam we probably can't rule out seismic failure.

Otherwise, seismic failure is highly dependent on the structure condition and original design. If the downstream slope is steeper than say 0.7 or 0.75 a dam is more prone to seismic failure. And of course, a dam in poor structural condition is more prone to seismic failure.

It may be appropriate to rule out seismic failure of a concrete dam is if the dam has been upgraded in the last 25-years or so using modern analysis techniques.

'Sunny-Day' Failure

Discuss 'sunny-day' failure evaluation approach.

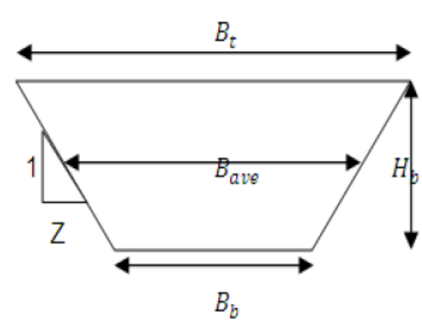
Breach Formulation

Empirically-Based Methods

Categories 1 and 2, above, are only useful for estimating peak dam breach outflow rates at the dam site. 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 1 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)



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- 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

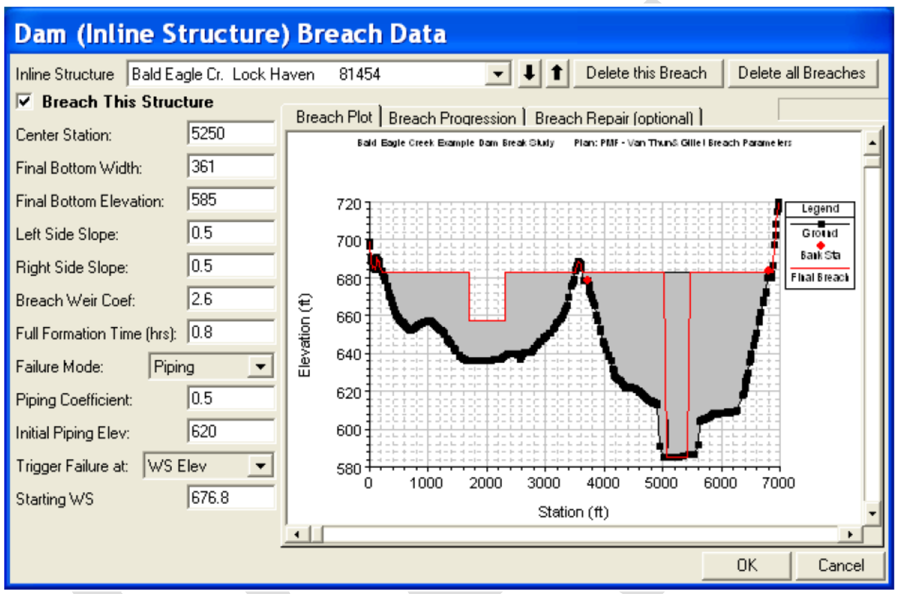

Figure 4 - HEC-RAS Dam Breach Editor

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. Following a recommendation by Wahl (2008), Xu and Zhang (2009) developed equations to computer 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 recorded breach events.

Additional Considerations 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

NWS BREACH

NRCS SITES or WinDAM

Uncertainty in Estimating Breach Parameters

xxxx

Apply alternative approaches and a range of conditions

Breach Hydrograph Routing

Hydrologic (HEC-1 and HEC-HMS)

See previous section.

Hydraulic (HEC-RAS)

2-Dimensional

Other Breach Models

- Harris and Wagner (1967)
- DAMBRK (NWS, Fread, 1977)
- FLDWAV (NWS)
- Lou (1981)
- BREACH (Fread, 1988)
- BEED (Singh and Scarlotos, 1985)
- FLOW SIM 1 & 2 (Bodine)
- FLO-2D
- HEC-RAS Unsteady (Dynamic Wave)
- HEC-HMS (Kinematic Wave)
- SITES/WinDAM (for assessing head-cutting of overtopping situations)
- HEC-HMS (Kinematic Wave)
- MIKE by DHI MIKE 11 1D and MIKE 21 – 2D integrated unsteady flow models with dam breach simulation
- Infoworks RS and ICM by Innovyze – Fully integrated hydrologic/hydraulic unsteady flow models with dam breach

Recognized Industry Experts

- Dr David S. Bowles – Utah State
- Tony L. Wahl, PE. Hydraulic Engineer Bureau of Reclamation Hydraulic Investigations and Laboratory Services Group Denver, Colorado.
- Dr. John England Bureau of Reclamation, Technical Service Center

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