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NRC Interim Staff Guidance on Estimating Flooding Hazards Due to Dam Failure

JLD-ISG-2013-01

Public Meeting

May 2, 2013

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UNITED STATES NUCLEAR REGULATORY COMMISSION
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Presentation Outline

- Accessing and Commenting on ISG *
- Schedule
- Purpose of Dam Failure ISG
- Sources of Guidance
- Content of ISG

*ISG= Interim Staff Guidance

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Accessing and Commenting

- Please refer to Docket ID NRC–2013–0073 when contacting the NRC
- JLD-ISG-2013-01 published in Federal Register
  - Federal Register / Vol. 78, No. 80 / Thursday, April 25, 2013 / Notices (pp 24439-24441)
  - Comment period closes on May 28th 2013
- Federal Rulemaking Web site:
  - *http://www.regulations.gov*
  - *Search* for Docket ID NRC–2013–0073.
- NRC's Agency-wide Documents Access and Management System (ADAMS):
  - *http://www.nrc.gov/readingrm/adams.html.*
  - ADAMS Accession No. ML13057A863
- NRC's Public Document Reading Room
  - Room O1–F21, One White Flint North, 11555 Rockville Pike, Rockville, Maryland 20852.

ISG Schedule

- 4/25/13 – Draft Issued for Public Comment
    - ISG noticed in the Federal Register for comment
- 5/2/13 – NRC Public Meeting on Draft ISG
- 5/28/13 – Close of Public Comment Period
- 6/7/13 – Issue Final ISG

Purpose of Dam Failure ISG

- Per NRC regulations, nuclear power plant licensees must determine the effects of potential flooding at their site from all credible potential mechanisms, including potential dam failures

- Consideration of potential upstream dam failure(s) is necessary to understand the total nuclear risk and to appropriately establish the nuclear power plant's licensing basis

- This ISG supplements existing NRC guidance and standard review plans

- This ISG provide guidance on approaches and methods acceptable to the NRC staff for reevaluating flooding hazards due to dam failure for the purpose of responding to enclosure 2 of the March 12, 2012, Request for Information (ADAMS Accession No. ML12053A340).

Sources Used

- Based mainly on guidance and technical references developed by federal agencies
  - FEMA
    - Federal Guidelines for Inundation Mapping of Flood Risks Associated with Dam Incidents and Failure
    - Selecting and Accommodating Inflow Design Floods for Dams
    - Earthquake Analysis and Design of Dams

Sources Used (Cont.)

- USACE
  - Safety of Dams – Policy and Procedures
  - Engineering Design – Design and Construction of Levees
  - Engineering Design – Retaining and Flood Walls
- USBR
  - Dam Safety Risk Analysis Best Practices Training Manual
- Others
  - State of Colorado Dam Breach Analysis Guidelines
  - NEI Draft White Paper

Dam Failure ISG Content

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2. Background
3. Simplified Modeling Approaches
4. Hydrologic Failure
5. Seismic Dam Failure
6. Sunny-Day Failure
7. Operational Failures and Controlled Releases
8. Dam Breach Modeling
9. Levee Breach
10. Flood Wave Routing

1. Introduction

- 1.1 Purpose
- 1.2 Scope
- 1.3 Framework for Dam Failure Flood Hazard Estimation
- 1.3.1 Screening
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- 1.4 Failure Probability
- 1.4.1 Historical Dam and Levee Failure Rates
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- 1.5.1 Dam Safety Governance
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- 1.5.3 Obtaining Information on Dams and Levees
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1.2 Scope

- The March 2012 Information Request specified three Tiers for submittal of re-evaluated flooding hazards.
- Plants in Tier 1 should have already submitted their flood re-analysis by March 11, 2013 (unless an extension has been granted), which predates issuance of this ISG.
  - Therefore, this ISG is not strictly applicable to Tier 1 sites with completed flood re-evaluations, and their dam failure flood hazard evaluations will be reviewed using present-day guidance, as described in the Request for Information.
- This ISG is applicable to Tier 2 and Tier 3 sites, as well as most Tier 1 sites that have been granted an extension.
- Instances where Tier 1 sites have been granted a very short extension (e.g. a few weeks), will considered on a case-by-case basis.

1.3 Framework for Dam Failure Flood Hazard Estimation

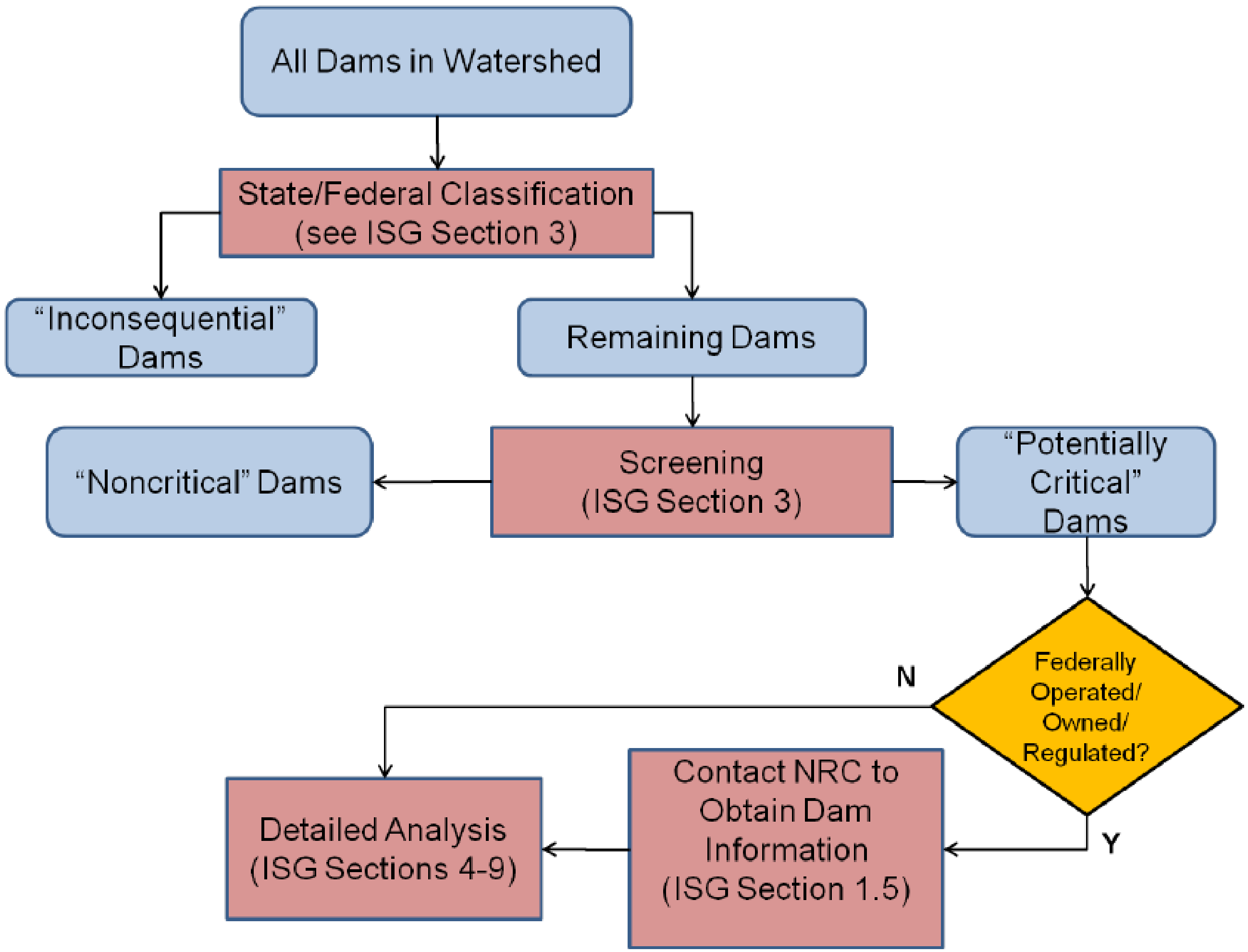

Figure 1. Levels of Analysis

1.3 Framework for Dam Failure Flood Hazard Estimation (Cont.)

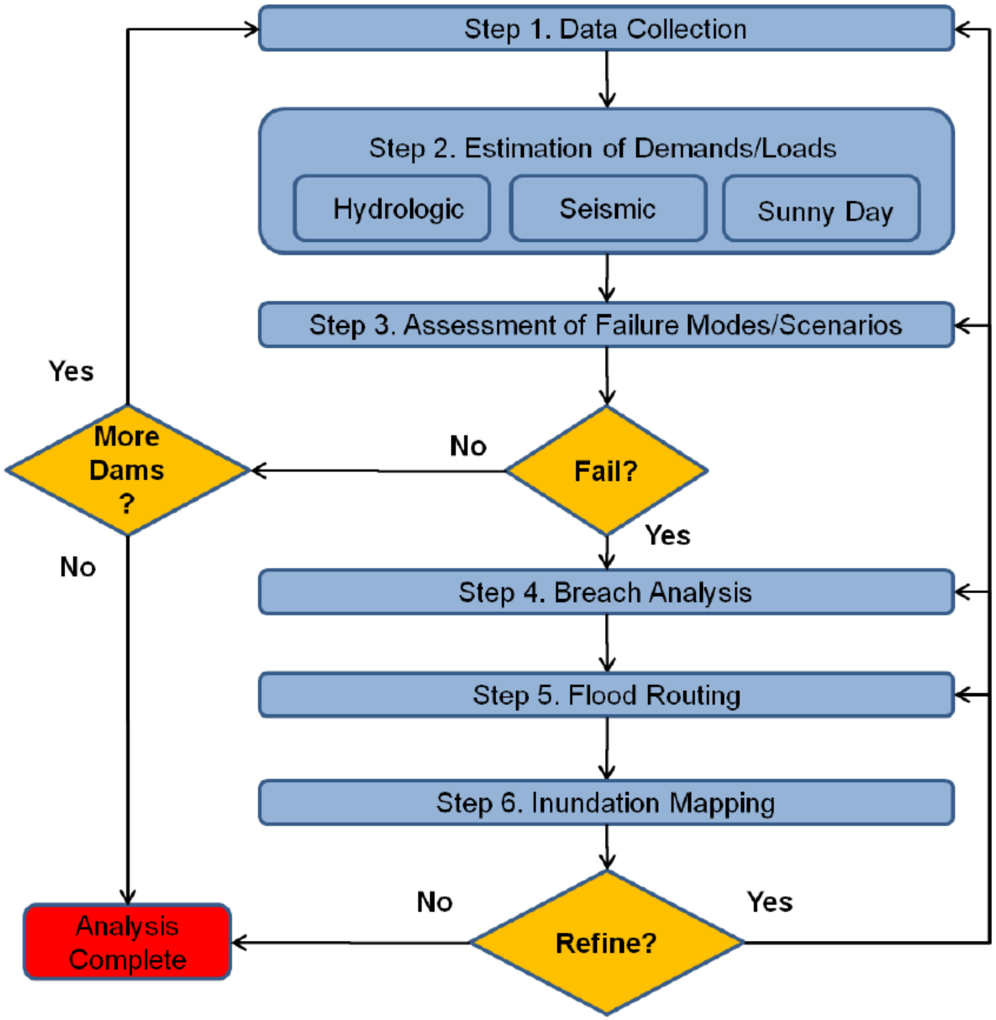

Figure 2. Overview of Detailed Dam Failure Flood Hazard Analysis

1.4 Failure Probability

- 1.4.1 Historical Dam and Levee Failure Rates
  - Expressed in terms of dam years, numerous studies of dam failures in the U.S. and worldwide have indicated an average failure rate on the order of 10^{-4} per dam year
  - Historical rates for dam failure provide useful information about generic failure probabilities. However, each dam and its environment are unique and failure probability estimates, if used, should be developed based upon site and dam specific data and information

1.4.2 NRC Approach to Man-made Hazards

- In general, both the probability of the hazard and the capacity/fragility of the dam would factor into the failure like hood determination. However, to the extent that the dam capacity or fragility is not known, more weight must be placed on the hazard probability.
- Therefore, the hazard probability target for judging the likelihood of a particular failure mode/scenario (either from a single hazard or appropriate combination) is $1x10^{-6}$ annual exceed probability with justification (i.e., dam failure may be excluded from further consideration if it can be shown by a dam specific engineering assessment that the probability of failure is 1x10-6 per year or less using current best practices).
- As of this writing, the methods discussed in the USBR Dam Safety Risk Analysis Best Practices Training Manual (USBR, 2011) are considered by the staff to represent current best practice. Therefore, the staff expects these risk results to be based on a thorough engineering analysis similar in scope and rigor to the comprehensive facility review process described in USBR (2011).

1.4.2 NRC Approach to Man-made Hazards (Cont.)

- When considering hydrologic failure due to large floods, extreme caution should be exercised with regard to attempts to estimate the probability of deterministic estimates such as the probable maximum precipitation (PMP) or probable maximum flood (PMF). Methods that involve extreme extrapolation of distributions such as log- Pearson and others based on limited data will be viewed with great skepticism.
- When considering seismic dam failure and probabilistic seismic hazard assessment (PSHA), it is important to note that the hazard of interest to the NPP is a catastrophic failure resulting in uncontrolled release of the reservoir, not lower levels of damage that may degrade the services that the dam provides. It is also recognized that the seismic design of dams typically includes significant margins and factors of safety. In order to account for this level of margin before failure, it acceptable to use the $1x10^{-4}$ annual frequency ground motions, at spectral frequencies important to the dam, for seismic evaluation of dams, instead of $1x10^{-6}$, as discussed above. However, appropriate engineering justification must be provided to show that the dam has sufficient seismic margin. Otherwise the $1x10^{-6}$ ground motions should be used.

1.5.3 Obtaining Information on Dams and Levees

- In the case of dams and levees owned or operated by U.S. federal agencies, the federal agency responsible (owner/operator) for the dam should be involved in any discussions, including possibly reviewing any analysis performed.
- Evaluation of dams is complex, requiring extensive expertise and site specific knowledge. It is critical for the owner/operator of the dam to assist NRC or its licensees when modifying the assumptions or methods used to developi the inundation maps for a specific area. If a federally owned dam is identified as critical to the flooding reanalysis, the licensee should contact NRC promptly.
- NRC will act as the interface between these agencies and licensees.
- Memoranda of Agreement or other mechanisms are being developed to facilitate sharing of data (including necessary safeguards to protect sensitive information) between NRC and the appropriate federal agencies.
- It is important to note that in many cases federal agencies that own or operate dams have conducted detailed failure analysis. To the extent these analyses are applicable, they should be used in the Recommendation 2.1 flooding reanalysis.

1.5.3 Obtaining Information on Dams and Levees (Cont.)

- In some cases, the dam or levee will be owned or operated by a private entity, but regulated by a federal agency. In this case, NRC will interface with the federal regulatory agency to obtain available information. Interactions between the licensee and the owner should be coordinated with NRC and the federal regulator.
- In most cases dams and levees will be owned and operated by private entities and regulated by a state agency. In this case, the licensee should interact directly with the owner and regulator. The licensee should notify NRC if they encounter difficulties in obtaining information. On a case-by-case basis, NRC may be able to provide some assistance in interfacing with state agencies.

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2. Background

- 2.1 Classification of Dams and Levees
- 2.1.1 Concrete Dams
- 2.1.2 Embankment Dams
- 2.1.3 Levees
- 2.2 Classification of Dam Failures
- 2.2.1 Influence of Dam Type on Failure Modes
- 2.2.1.1 Concrete Dams
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- 2.2.2 Failure of Spillways, Gates, Outlet Works, Appurtenances
- 2.2.3 Operational Failures and Controlled Releases
- 2.3 Multiple Dam Failures

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3. Simplified Modeling Approaches

- 3.1 Criteria for “Inconsequential” Dams
- 3.2 Simplified Modeling Approaches
- 3.2.1 Representing Clusters of Dams

3.1 Criteria for "Inconsequential" Dams

- Dams identified by the USACE as meeting the requirements described in Appendix H (Dams Exempt from Portfolio Management Process) of ER 1110-2-1156, "Safety of Dams – Policy and Procedures", (USACE, 2011c) may be removed from consideration for site impacts.
- Dams identified by other federal or state agencies as having minimal or no adverse failure consequences beyond the owner's property may be removed from consideration.
- Dams owned by licensees may not be removed.
- Other inconsequential dams may be removed with appropriate justification (e.g. can be easily shown to have minimal or no adverse downstream failure consequences).

3.2 Simplified Modeling Approaches (Cont.)

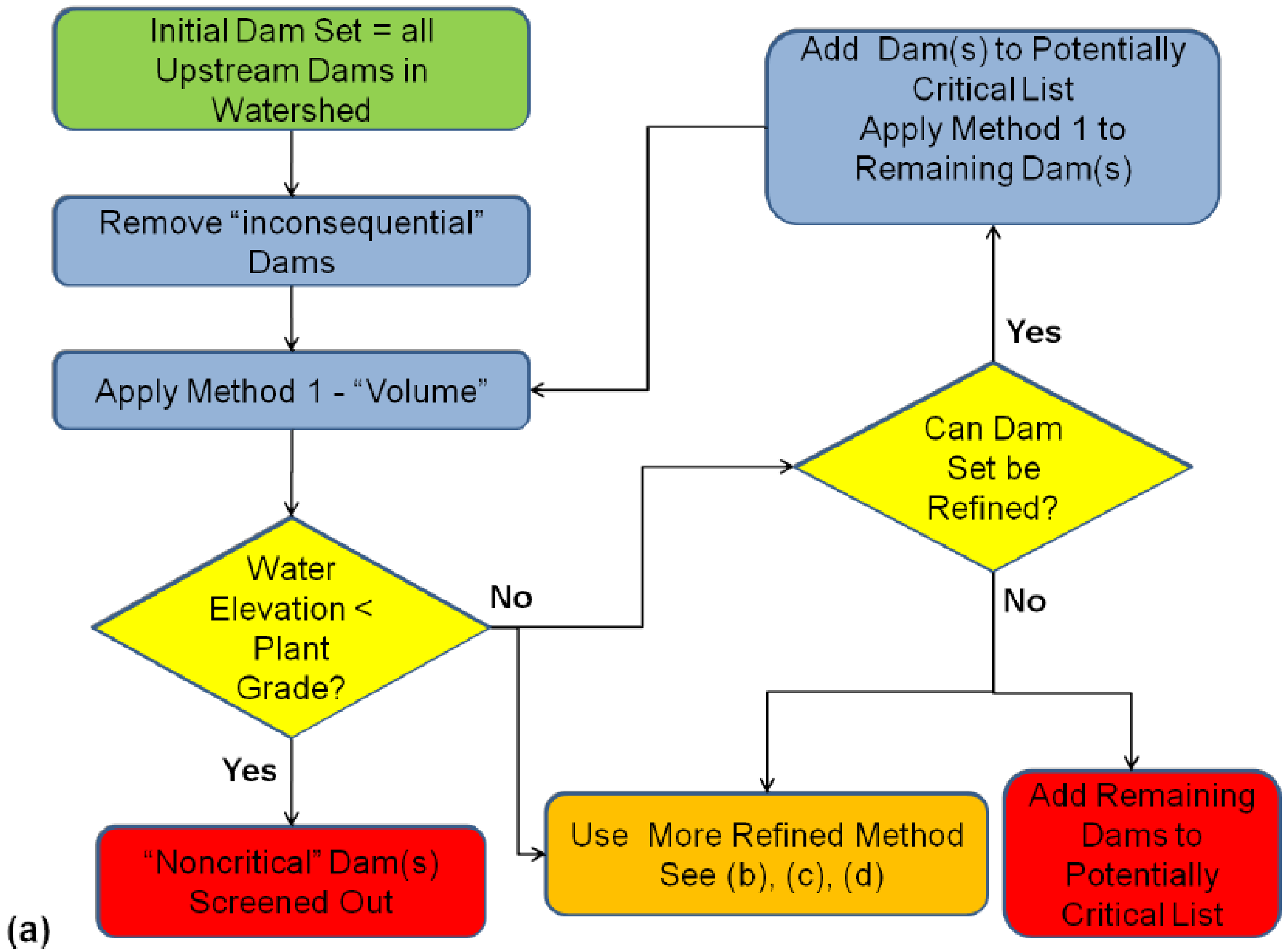

Figure 10. Screening Method Flowchart (a) – Method 1 (Volume)

3.2 Simplified Modeling Approaches (Cont.)

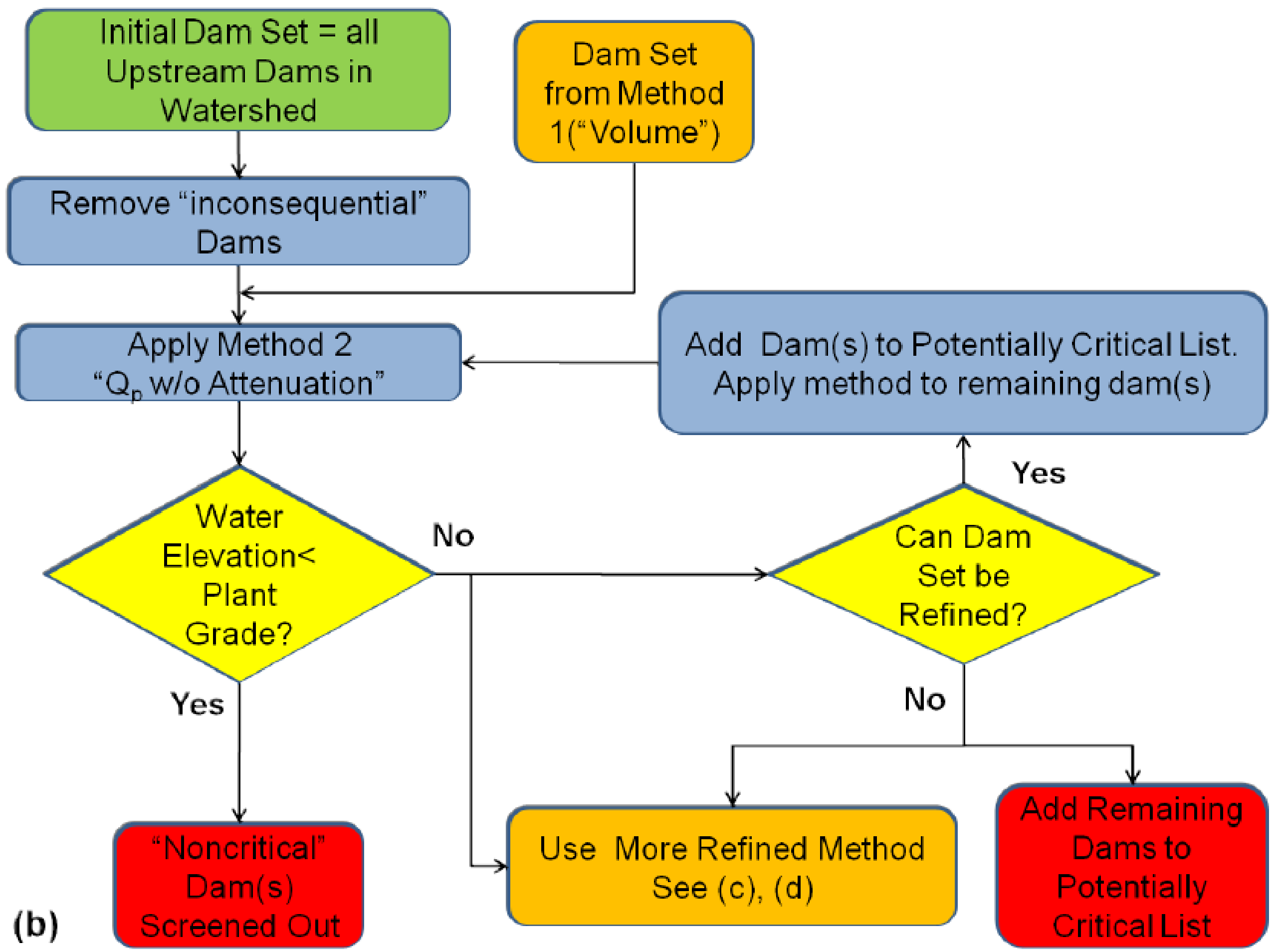

Figure 11. Screening Method Flowchart (b) – Method 2 (Peak Flow without Attenuation)

3.2 Simplified Modeling Approaches (Cont.)

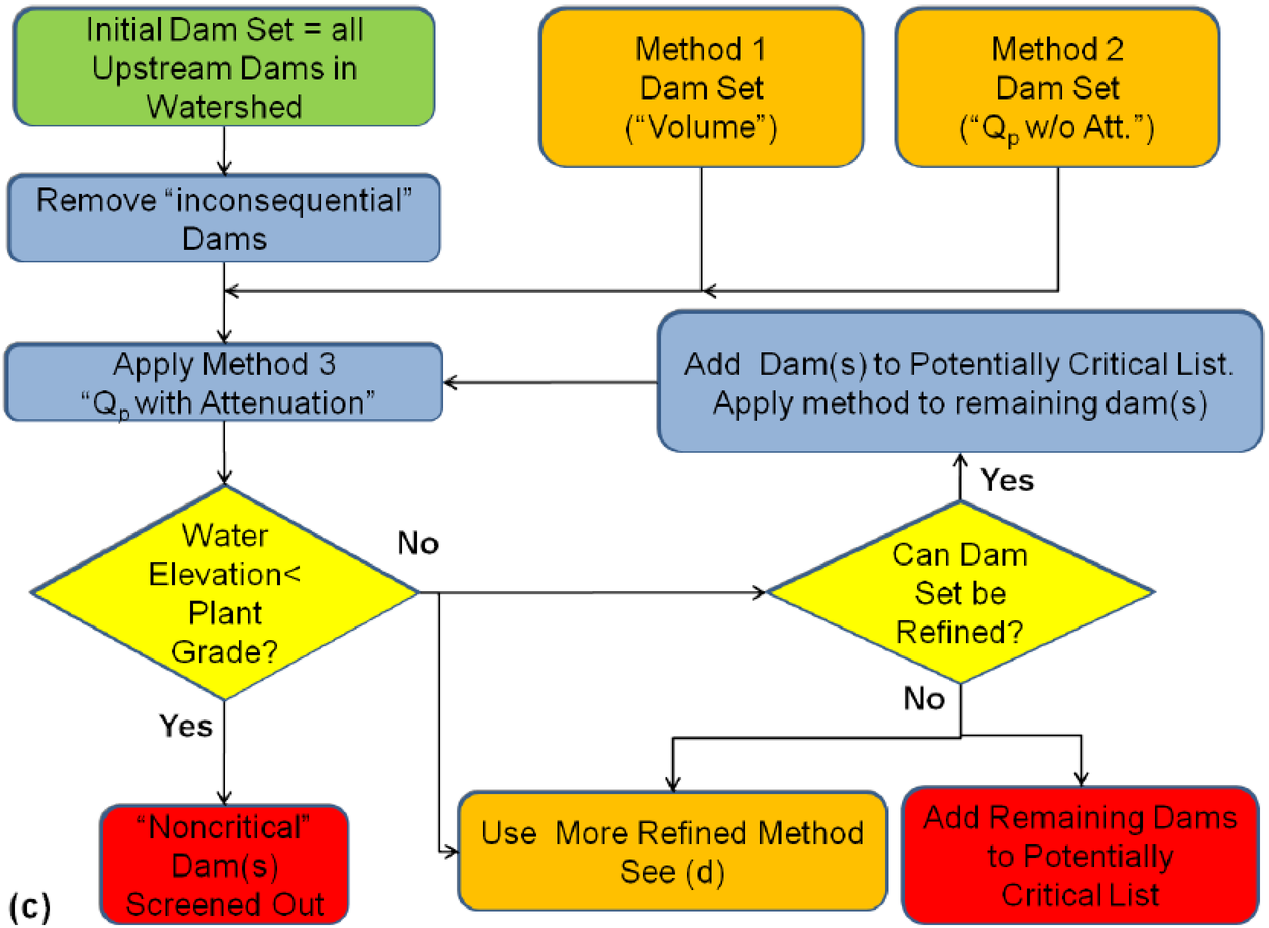

Figure 12. Screening Method Flowchart (c) – Method 3 (Peak Flow with Attenuation)

3.2 Simplified Modeling Approaches (Cont.)

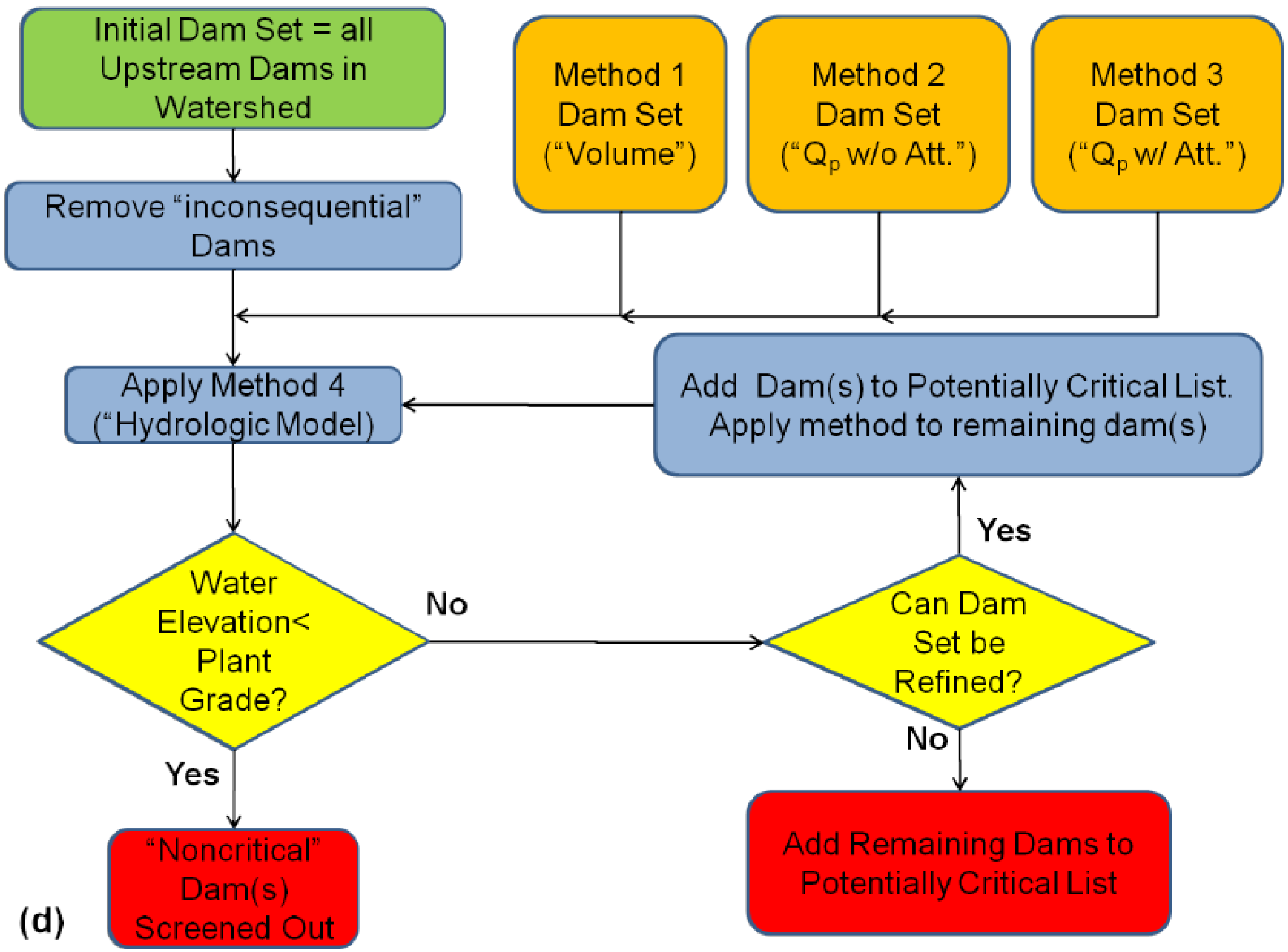

Figure 13. Screening Method Flowchart (d) – Method 4 (Hydrologic Method)

3.2.1 Simplified Modeling Approaches (Cont.)

Dam	Location of hypothetical dam	Comment
Dams 1, 2 and 3	DS of 1, 2 and 3	Illustrated in Figure 14
Dams 1 and 2	At or DS of 2	Dam 2 is closer to site
Dams 1 and 3	At or DS of 3	Dam 3 is closer to site.
Dams 2 and 3	At or DS of 2	Dam 2 is closer to site.

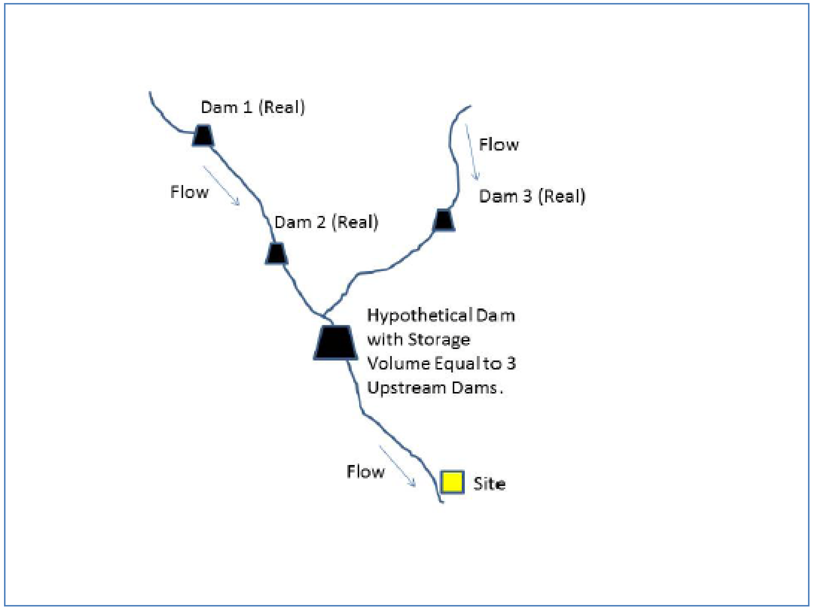

Figure 14. Hypothetical Dam Representing Storage Upstream

4. Hydrologic Dam Failure

- 4.1 Hydrologic Failure by Structure Type
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- 4.1.2 Embankment Dams
- 4.1.3 Spillways, Gates, Outlet Works and Other Appurtenances
- 4.1.4 Levees
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- 4.2.1 Internal Pressure
- 4.2.2 Overtopping
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- 4.2.2.2 Starting Reservoir Elevation
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- 4.2.2.4 Spillway Discharge Capacity
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- 4.2.4 Surface Erosion from High Velocity and Wave Action
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- 4.2.6 Failure of Gates
- 4.2.7 Debris
- 4.2.7.1 Mud/Debris Flows
- 4.2.7.2 Waterborne Debris
- 4.2.8 Multiple Dam Failure due to Single Storm Scenario
- 4.2.9 Levee Failures

4.1.1 Concrete Dams

- Concrete dams should be evaluated for potential hydrologic failure modes including, but not limited to:
  - overtopping of the main dam, overtopping erosion of a dam abutment or foundation
  - erosion of an unlined tunnel or spillway chute
  - erosion of a channel downstream from a stilling basin due to flow in excess of capacity
  - erosion of the spillway foundation where floor slabs have been damaged or lost
  - overstressing of the dam, foundation, or abutments
  - cavitation damage to spillway and outlet flow surfaces

4.1.2 Embankment Dams

- Embankment dams should be analyzed for conditions leading to and the effects of:
  - Overtopping
  - Increases in internal seepage pressures

- Analysis of hydrologic failure modes should consider the potential for loss or degraded function of spillways, gates, outlet works and other appurtenances. If failure is not assumed, provide an engineering justification.

4.1.3 Spillways, Gates, Outlet Works and Other Appurtenances

- Analysis of hydrologic failure modes should consider the potential for loss or degraded function of spillways, gates, outlet works and other appurtenances.
- If failure is not assumed, provide an engineering justification.

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4.1.4 Levees

- In general, earthen embankment levees should be assumed to fail when overtopped.
- The case for nonfailure must be developed using detailed engineering analysis supported by site-specific information, including material properties of the embankment and foundation soils, material properties of embankment protection (if any), levee condition, etc.
- Other forms of levees (e.g., pile walls, concrete flood walls) should be evaluated for potential failures applicable to the particular type of levee.

4.1.4 Levees(Cont.)

- Levees are generally not designed to withstand high water levels for long periods.
  - No generally accepted method for predicting how long a levee will continue to function under high loading conditions.
  - Historical information is the best available basis for predicting levee performance. The historical information should be from levees that have similar design and construction characteristics as the levee being analyzed.
- The potential for loss or degraded function of levee control works should be considered.
- Because levees are typically designed to function as a system, the potential for failure of an individual segment should be evaluated for its impact on the functioning of the levee system as whole.
- Levees should not be assumed to fail in a beneficial manner without appropriate justification.

4.2.1 Internal Pressure

- Dams should be evaluated for potential failures due to internal pressures from a hydrologic inflow event (flood).
- Potential failure modes that should be evaluated include deterioration or plugging of drains and internal erosion mechanisms.
  - Evaluation should generally include reviewing the dam design to assure that appropriate filters, drains, and monitoring points are included.
  - Monitoring records of piezometers, observation wells or other observation methods can be used to show absence of unremediated deficiencies.

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4.2.2 Overtopping

- Dams unable to pass their individual PMF should be considered for failure.
- Embankment dams should generally be assumed to fail when overtopped. If failure is not assumed when a dam is overtopped, justification should include detailed engineering analysis supported by site-specific information, including material properties of the embankment and foundation soils, material properties of embankment protection (if any), dam condition, etc.
- Concrete dams are not assumed to fail due to minor overtopping, but must be evaluated for failure due to loss of foundation or abutment support. Impact of the flood flows on structures such as tunnels, spillways, chutes and stilling basins should be examined.
- The potential for overtopping due to nonfunctioning gates, outlets and other appurtenances should be evaluated to determine the appropriate failure assumptions with appropriate engineering justification.

4.2.2 Overtopping(Cont.)

- **4.2.2.2 Starting Reservoir Elevation**
  – The default starting water surface elevation used in flood routings for evaluation of overtopping is the maximum normal pool elevation. Other starting water surface elevations may be used, with appropriate justification. Justification may include the operating rules and history of the reservoir. For example, if the flood being considered is associated with a distinct season and the operation of the dam has seasonal variations that are codified and have historically been followed, then it may be reasonable to select a starting reservoir elevation consistent with the operating rules and history. But consideration should be given to possible instances where the operating history and/or rules have been influenced by anomalous conditions such as drought
- **4.2.2.3 Reservoir Surcharge Capacity**
  – Reservoir surcharge capacity can be credited in flood routings for evaluation of overtopping, with appropriate justification and documentation.

4.2.2 Overtopping(Cont.)

- **4.2.2.4 Spillway Discharge Capacity**
  - Release capacity through appurtenances other than the spillway (e.g., outlets, turbines) may be credited as part of the total available release capacity, with appropriate engineering justification that these appurtenances will be available and remain operational during a flood event. Access to the site during a flood event should be considered.
  - The generators and transmission facilities to support the credited turbine(s) must be shown to be operational under concurrent flood and expected prevailing weather conditions if the turbines are credited as part of the total available release capacity. However, at least one turbine should always be assumed to be down (e.g. for maintenance or other reasons) in performing flood routings.
  - The potential for flood-borne debris to reduce spillway capacity should be considered. Use historical information to assess debris production in the watershed. Describe structures, equipment and procedures used to prevent spillway blockage by waterborne debris.
- **4.2.2.5 Wave Action**
  - Overtopping due to wave action should be evaluated, in addition to stillwater levels. Coincident wind waves should be estimated at the dam site based on the longest fetch length and a sustained 2-year wind and added to the stillwater elevation.

4.2.3 Structural Overstressing of Dam Components

- Static stability of the dam and key appurtenances under hydrologic loads associated with the dam's PMF should be demonstrated using current methods and standards.
- If the dam cannot withstand the applied loads, the dam should be assumed to fail.
- If the appurtenance cannot withstand the load, assume failure of the appurtenance and estimate impact of its failure on stability of the dam.
  - If the dam stability is not impacted, one still must consider the downstream impact of uncontrolled release (if any) associated with appurtenance failure.

4.2.4 Surface Erosion from High Velocity and Wave Action

- Surface erosion of earthen embankments, spillways, channels, etc. due to wave action, high velocity flows, and ice effects should be considered.

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4.2.5 Failure of Spillways

- Dams should be evaluated for potential failure due to spillway failure.
- Concrete spillways should be evaluated for relevant failure modes including stagnation pressure failures, cavitation, concrete deterioration (e.g., delamination, alkali-silica reaction, freeze-thaw damage and sulfate attack) and other relevant modes.
- Other (non-concrete) spillways should be evaluated for potential failures including failure of the grass or vegetation cover in the spillway; concentrated erosion that initiates a headcut; deepening and upstream advance of the headcut; and other relevant modes.

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4.2.6 Failure of Gates

- The evaluation should consider the potential for gate failure under flooding conditions to lead to an uncontrolled release of the reservoir.
- With regard to fuse plugs, one should consider uncertainty about the exact depth and duration of overtopping needed to initiate breach and the uncertainty about the exact rate of breach development. (note typo in draft ISG)

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4.2.7 Debris

- **4.2.7.2 Waterborne Debris (equation mangled in PDF)**

$$F_i = wV/g\Delta t$$

where F_i is the impact force, w is the weight of the object, V is the flood velocity, g is the acceleration of gravity, and Δt is the duration of the impact. The object is assumed to be at or near the water surface level when it strikes the building. Therefore, the object is assumed to strike the building at the stillwater level.

- The potential for a basin to generate mud/debris flows should be considered.
- Loads due to waterborne debris carried by flood waters should be considered with regard to impacts on the dam (i.e., gates and associated mechanical equipment, appurtenances, parapets, etc.).
- In the case of dam break flood waves, debris impacts to SSCs important to safety should be considered.
- In general, methods outlines in the FEMA Coastal Construction Manual and average size/weight for objects specified in ASCE Standards are acceptable.
- Licenses should consider regional and/or local conditions before the final debris weight is selected. On navigable waterways, for example, the potential for impact from water craft and barges should be considered in addition to trees, logs and common man-made objects.

4.2.8 Multiple Dam Failure due to Single Storm Scenario

- Potentially critical dams should be evaluated for potential of hydrologic dam failures to lead to cascading failures of downstream dams and simultaneous dam failures causing flood conditions at the site. Operational rules may be considered but the starting water surface elevation must be as specified in Section 4.2.2.1.
- Flood waves from multiple dam failures should be assumed to reach the NPP site simultaneously unless appropriate justification for differing flood arrival times is provided.
- Two cases of multiple dam failure should be considered: (1) failure of individual dams on separate tributaries upstream from the site and (2) cascading or domino-like failures of dams upstream from the site.

4.2.8 Multiple Dam Failure due to Single Storm Scenario (Cont.)

- Failure of individual dams on separate tributaries upstream from the site
  - One or more dams may be located upstream from the site but on different tributaries so the flood generated from the failure of an individual dam would not flow into the reservoir impounded by another dam. These individual dam failures should be analyzed together because of the potential for a severe storm to cause large floods on multiple tributaries.

4.2.8 Multiple Dam Failure due to Single Storm Scenario (Cont.)

- Cascading or domino-like failures of dams upstream from the site
  - Failure of an upstream dam may generate a flood that would become an inflow into the reservoir impounded by a downstream dam and may cause failure by overtopping of the downstream dam. If several such dams exist in a river basin, each sequence of dams within the river basin could fail in a cascade.
  - Each cascading failure sequences should be investigated to determine one or more sequences of dam failures that may generate the most severe flood at the site.
  - Simplified estimates of the total volume of storage in each of the potential cascades should provide a good indication of the most severe combination.
  - In multiple cascades that cannot be separated by simple hydrologic reasoning, all of the candidate cascades that are comparable in terms of their potential to generate the most severe flood at the site should be simulated using the methods described in Section 10
  - The most severe flood at the site resulting from these cascades should be considered in determining the design-basis flood.

4.2.8 Multiple Dam Failure due to Single Storm Scenario (Cont.)

- Scenarios
  - Depending on the storage capacities of the reservoirs impounded by dams in a given cascading scenario, it may be reasoned that the scenario that would release the largest volume of stored water may likely lead to the most severe flooding scenario.
  - Distance a flood has to travel to reach a plant site also may affect the severity of the flood at the site.
  - If a definite conclusion cannot be reached, all possible cascading scenarios should be simulated to determine the most severe scenario.

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4.2.9 Levee Failures

- If the performance of levees is potentially important to estimation of inundation at the NPP site, failures should be treated in a conservative manner, but realistic manner.
- If credit is taken for a specific levee behavior (either failure or nonfailure), engineering justification should be provided.
- Assumptions regarding conveyance and off-stream storage should be supported with engineering justifications.

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5. Seismic Dam Failure

- 5.1 Overview
- 5.2 Seismic Failure by Structure Type
- 5.2.1 Concrete Dams
- 5.2.2 Embankment Dams
- 5.2.3 Spillways, Gates, Outlet Works and Other Appurtenances
- 5.2.4 Levees
- 5.3 Analysis of Seismic Hazards Using Readily Available Tools and Information
- 5.3.1 Ground Shaking
- 5.3.2 Fault Displacement
- 5.3.3 Liquefaction
- 5.4 Assessment of Seismic Performance of Dams Using Existing Studies
- 5.4.1 Ground Shaking
- 5.4.2 Fault Displacement
- 5.4.3 Liquefaction
- 5.5 Multiple Dam Failure Due to a Single Seismic Event
- 5.6 Modeling Consequences of Seismic Dam Failure
- 5.7 Detailed Site Specific Seismic Hazard Analysis
- 5.8 Detailed Analysis of Seismic Capacity of the Dam

5.1 Overview

- PSHA is considered to be the state of practice for evaluating seismic hazards for dam failure

5.1 Overview (Cont.)

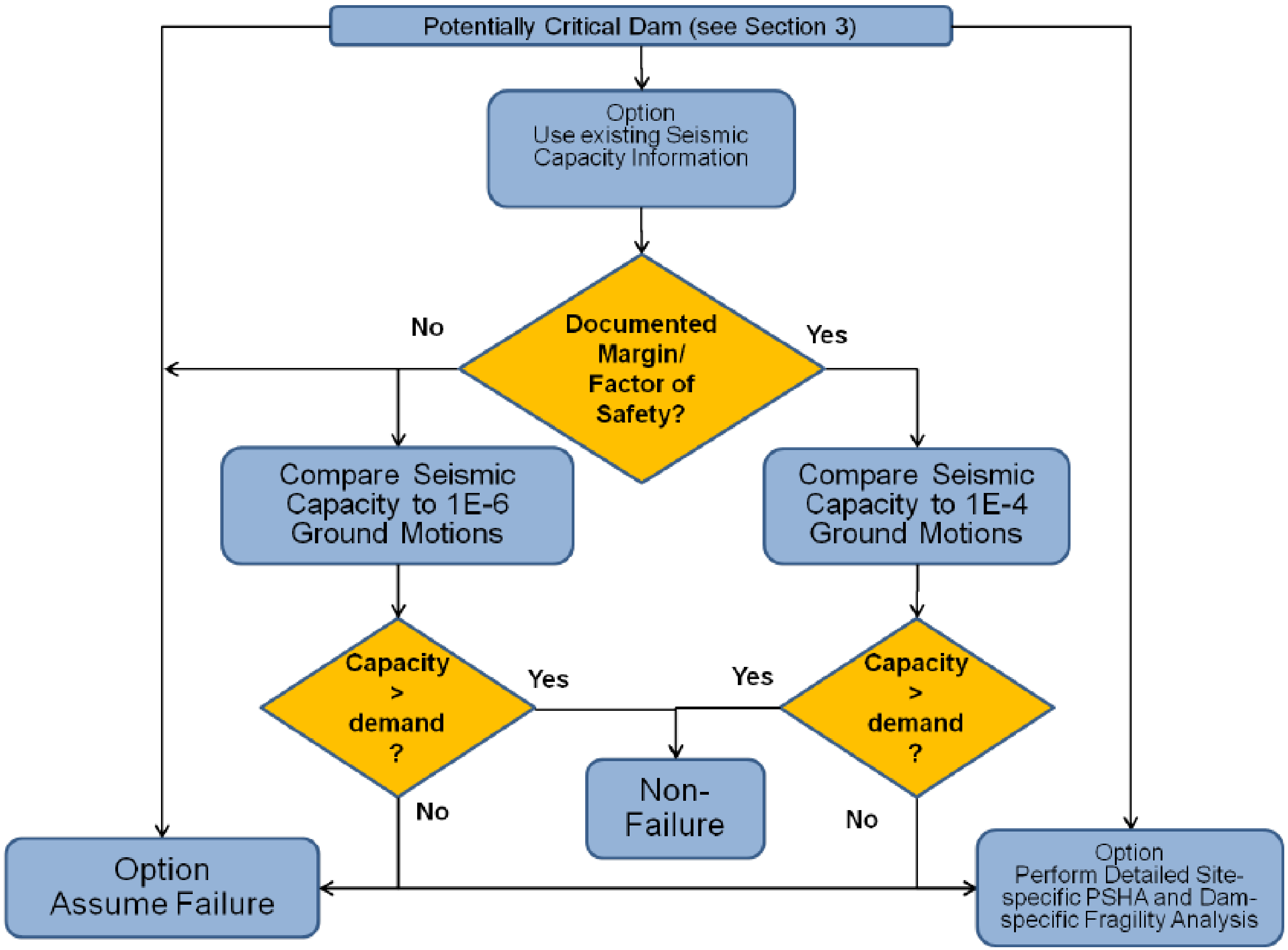


Figure 15. Seismic Dam Failure Analysis Options

5.2 Seismic Failure by Structure Type

- Concrete Dams
  - Seismic analysis of concrete dams should include assessment of ground shaking, surface displacement, and forces due to water in the reservoir.
  - Both structural and foundation failure modes should be considered.
  - Foundation liquefaction/deformation potential should be considered.
  - Structural failure modes considered should take into account the unique concerns for the type of dam in question.
- Embankment Dams
  - Seismic analysis of embankment dams should include assessment of ground shaking and surface displacement.
  - Both structural and foundation failure modes should be considered.
  - Deformation and liquefaction potential of both the dam and the foundation should be considered.

5.2 Seismic Failure by Structure Type (Cont.)

- **Spillways, Gates, Outlet Works and Other Appurtenances**
  - Seismic evaluation of dams should include consideration of whether a seismic event could lead to dam failure and subsequent uncontrolled release of the reservoir due to loss or degraded function of spillways, gates, outlet works and other appurtenances.
- **Levees**
  - Survival of a loaded levee during an earthquake event should be justified through appropriate engineering analysis.
  - Levees should not be assumed to fail in a beneficial manner, without appropriate engineering justification.

5. Seismic Dam Failure (Cont.)

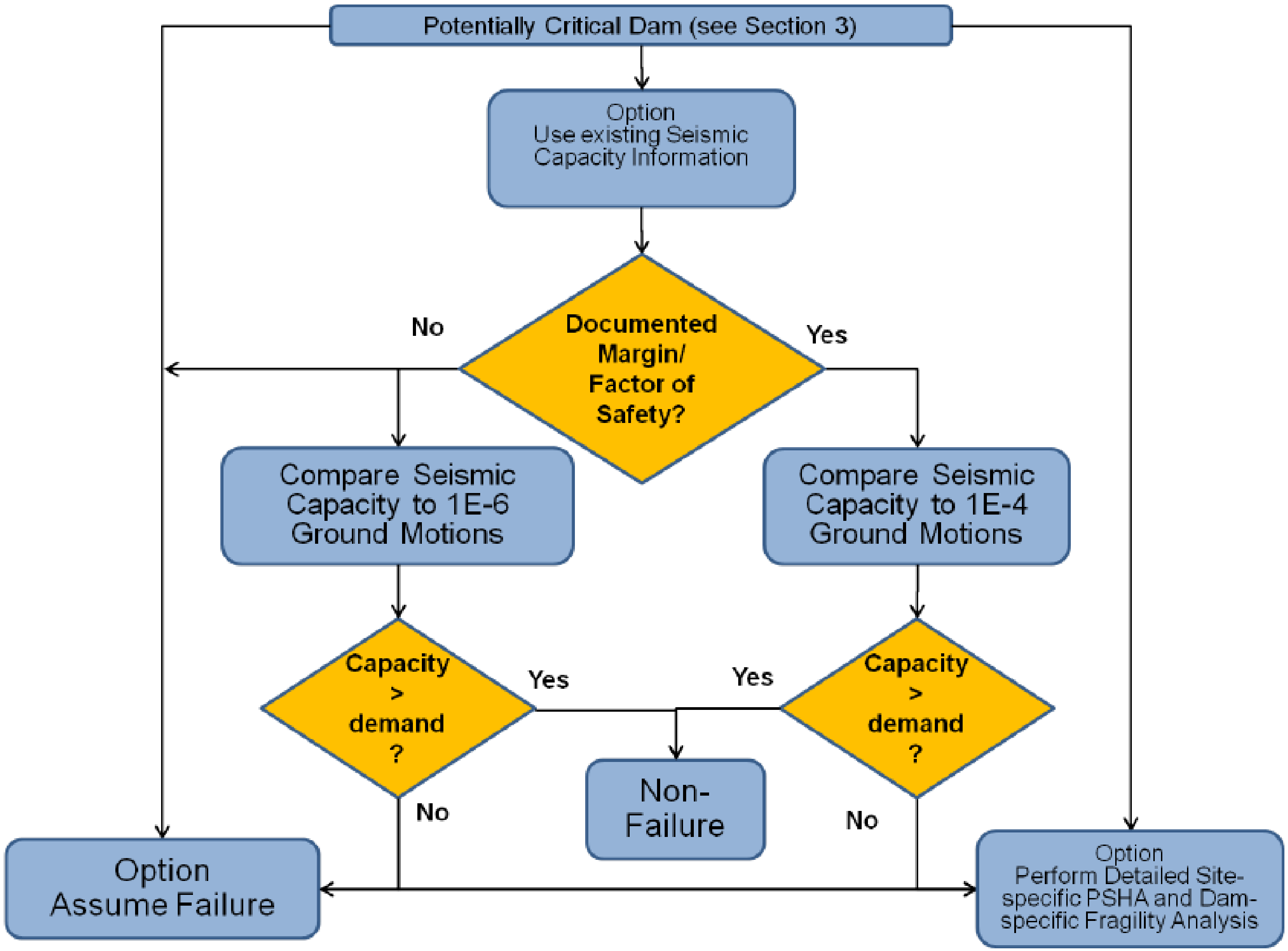


Figure 15. Seismic Dam Failure Analysis Options

5.3 Seismic Hazard Analysis Using Readily Available Tools and Information

- **5.3.1 Ground Shaking**
  - The seismic hazard at the dam site should be characterized using probabilistic seismic hazard assessment (PSHA) for the spectral frequencies of interest to the dam:
    - The data and software tools available from USGS, which were used to develop the most recent version of the National Seismic Hazard Maps (this is the 2008 version as of the publishing of this guidance) are suitable for developing bedrock hazard curves and uniform hazard spectra at 1×10^{-6} annual frequency of exceedance. (USGS, 2008)
    - The site amplification functions developed by the Electric Power Research Institute (EPRI, 1989) should be used to perform a site response analysis as described in NUREG/CR-6728 (USNRC, 2001).
  - As an alternative to use of the USGS seismic hazard curves, it is acceptable to performance a site-specific PSHA consistent with the methodologies suitable for use in characterizing seismic hazard at U.S. nuclear power plant sites, as described in Regulatory Guide 1.208 (USNRC, 2007).

<u>5.3 Seismic Hazard Analysis Using Readily Available Tools and Information (Cont.)</u>

- **5.3.2 Fault Displacement**
  - Dam sites should be evaluated for the potential for surface fault displacement to cause damage to the dam.
  - The potential for primary and secondary surface faulting should be considered.
  - It is acceptable to utilize existing analyses that demonstrate that a dam is not susceptible to fault displacement.

5.3 Seismic Hazard Analysis Using Readily Available Tools and Information(Cont.)

- **5.3.3 Liquefaction**
  - The dam site should be evaluated for liquefaction potential.
  - Regulatory Guide 1.198 provides guidance on acceptable methods for evaluating the potential for earthquake-induced instability of soils resulting from liquefaction and strength degradation.

5.4 Seismic Performance Analysis Using Existing Studies

- **5.4.1 Ground Shaking**
  - The seismic demands on the structure should be defined using the site-specific hazard spectrum (based on the UHRS and accounting for site amplification) as described in Section 5.4.1. The design spectrum (or spectrum determined by other seismic analyses) is compared against the site-specific hazard spectrum to assess the failure potential of the dam. If the capacity of the structure exceeds the site-specific seismic demands at the spectral frequencies of relevance to the dam, with appropriate margin to account for uncertainties in the analysis, the dam can be assumed not to fail due to seismic ground shaking.
  - In cases where information does not exist to characterize the capacity of the dam by response spectrum or define capacities at the frequencies of relevance to the dam (e.g., in the case when the dam design was based on pseudo-static analysis using a single demand such as peak ground acceleration and the dam has not been reevaluated to define capacity in terms of other intensity measures), the licensee may leverage such analysis with appropriate justification. Examples of appropriate justification include demonstration of the conservatism and applicability of the analysis, in light of the UHS developed in Section 5.4.1 including effects of site amplification of a range of spectral frequencies.
  - Dams that cannot be shown to have sufficient capacity should be assumed to fail and breach parameters computed as described in Section 7 Moreover, dams that are susceptible to seismic failure should be evaluated for the potential for multiple dams to fail during a single seismic event as described in Section 5.5. Alternatively, it is acceptable to perform more detailed assessment of the performance of the dam (i.e., performing new assessments) as described in Section 5.8.

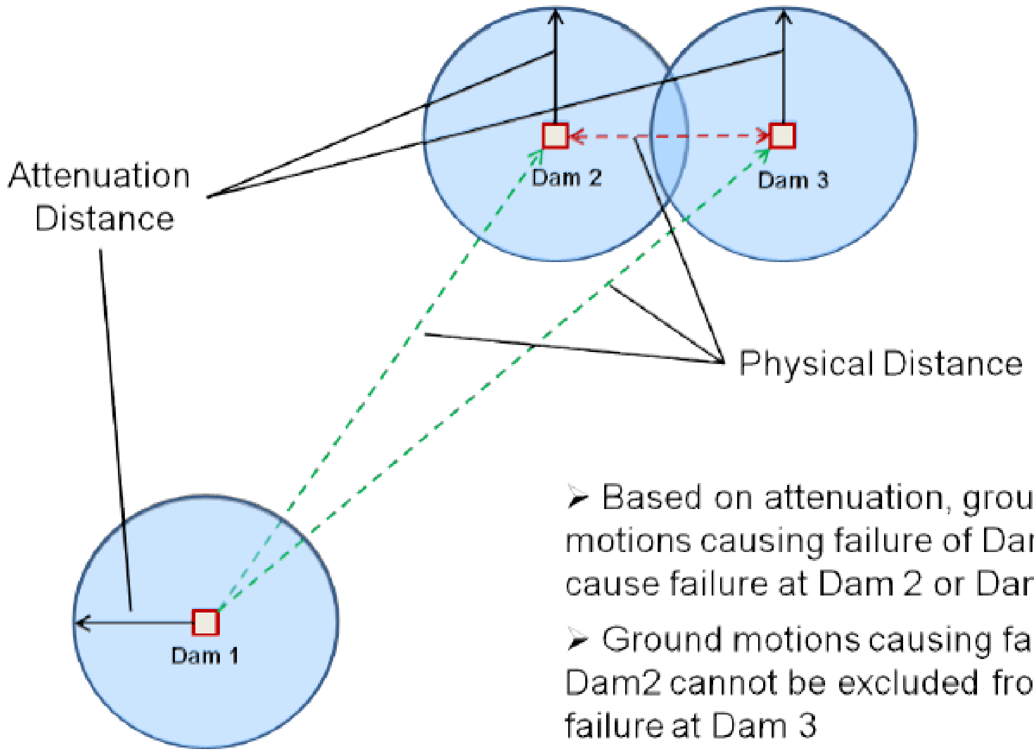
5.4 Seismic Performance Analysis Using Existing Studies

- **5.4.2 Fault Displacement**
  - Existing studies or data on dam or foundation materials can be used to assess performance of the dam with respect to surface displacement, in light of the seismic hazard defined for the site, with appropriate justification of their applicability and with appropriate conservatism to account for uncertainties.
- **5.4.3 Liquefaction**
  - Existing studies or data on dam or foundation soils can be used to assess performance of the dam with respect to liquefaction or loss of strength, in light of the seismic hazard defined for the site, with appropriate justification of their applicability and with appropriate conservatism to account for uncertainties.

5.5 Multiple Dam Failure Due to a Single Seismic Event

- Set of dams that are vulnerable to failure at or below the ground motion level associated with a 1E-4 annual frequency of exceedance.
- Hierarchical Approach
  - Using knowledge about the attenuation of ground motion with distance relative to the distance between dams
  - Refinement through deaggregation of the seismic hazard

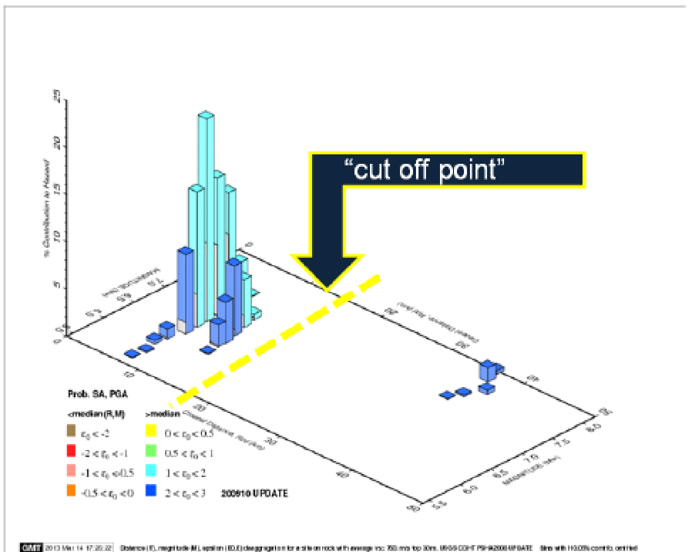
5.5 Multiple Dam Failure Due to a Single Seismic Event (Cont.)



- Based on attenuation, ground motions causing failure of Dam 1 do not cause failure at Dam 2 or Dam 3.
- Ground motions causing failure at Dam2 cannot be excluded from causing failure at Dam 3
- Ground motions causing failure at Dam2 cannot be excluded from causing failure at Dam 3

Figure 16. Using Knowledge about the Attenuation of Ground Motion with Distance

5.5 Multiple Dam Failure Due to a Single Seismic Event (Cont.)



Source: USGS

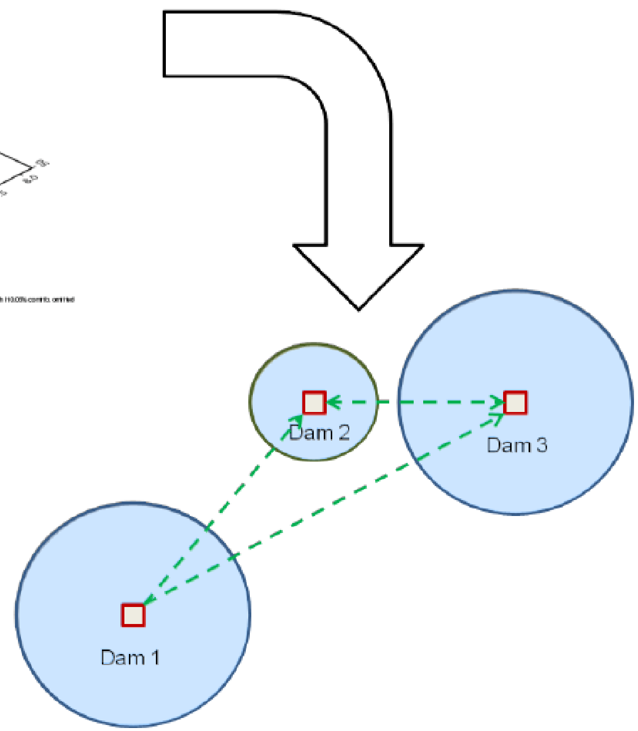


Figure 17. Refinement of Seismic Influence Using Deaggregation

5.6 Modeling Consequences of Seismic Dam Failure

- Dam failure due to an earthquake should be considered for both the maximum normal operating (“full-pool”) and average reservoir levels. Normal, non-flood tailwater conditions should be used.
- Reservoir and downstream tributary inflows should be seasonally consistent with the selected reservoir level.
- Given the hazard frequency target of 1×10^{-6} discussed in Section1.4.2, the dam failure flood wave at the site should be combined with flows of a frequency that result in a combined annual probability of 1×10^{-6}. For example, if the dam fails under a 10^{-4} ground motion, combine the dam break flood wave with a 100-year flood. If the dam fails under a 10^{-3} ground motion, combine the dam break flood wave it with a 1000-year flood.

5.7 Detailed Site Specific Seismic Hazard Analysis

- Because each dam and its immediate environment form a unique system, it is not feasible to provided detailed guidance that will be applicable in all cases. Therefore, detailed, site-specific seismic hazard analyses will be reviewed on a case-by-case basis. The following discussion is meant to provide a general overview of the pieces that would normally be part of a detailed seismic hazard evaluation
- Ground motion prediction equations approved by the NRC for Recommendation 2.1 Seismic are acceptable for use in dam failure analysis for Recommendation 2.1 Flooding.

5.8 Detailed Analysis of Seismic Capacity of the Dam

- **5.8.1 Concrete Dams**
  - Pseudostatic methods are generally discouraged from use in stability analysis of structures.
  - Structures that fail to meet prescribed pseudostatic stability requirements (i.e., sliding safety factors and resultant location) should be subjected to in-depth study using dynamic analyses to assess the performance of the dam and foundation during an earthquake.
  - Detailed evaluation of the seismic performance of a concrete dam should be performed using (as appropriate) linear-elastic response spectrum analysis, linear-elastic time-history analysis, or non-linear time-history methods. Guidance provided on these methods in FEMA Dam Safety Guidelines (FEMA, 2005) should be used to perform the evaluation.
  - A nonlinear analysis should be performed if the response of the dam would be influenced significantly by nonlinearity from material behavior or changes in geometry.
  - Detailed evaluation of the seismic performance of a concrete dam should be performed using (as appropriate) linear-elastic response spectrum analysis, linear-elastic time-history analysis, or non-linear time-history methods. Guidance provided on these methods in FEMA Dam Safety Guidelines (FEMA, 2005) should be used to perform the evaluation.

5.8 Detailed Analysis of Seismic Capacity of the Dam(Cont.)

- **Embankment Dams**
  - Detailed seismic evaluation of embankment dams should include the following (as appropriate): post-earthquake stability analysis, deformation analysis, and assessment of liquefaction potential.
  - If there are no potentially liquefiable materials present, evaluation can usually be done by the Newmark sliding-block approach. In situations where excess pore pressure could develop, more rigorous finite-element or finite-difference analyses should be conducted.
  - Embankment dams should be evaluated to ensure sufficient factors of safety against sliding of critical failure surfaces.
  - Embankment dams should be evaluated to ensure sufficient factors of safety against triggering of liquefaction.

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6. Other (Sunny Day) Failures

- 6.1 Overview of Sunny Day Failures by Structure Type
- 6.1.1Concrete Dams
- 6.1.2 Embankment Dams
- 6.2 Analysis of Sunny Day Failures
- 6.2.1 Probability of Sunny Day Failure Modes
- 6.2.2 Breach Analysis Initial Water Surface Elevation

6. Introduction

- Example causes/initiators
  - Deterioration of concrete (e.g., weathering, cracking, chemical growth)
  - Deterioration of embankment protection (e.g., grass cover, riprap, or soil cement)
  - Excessive saturation of downstream face or toe of embankment.
  - Excessive embankment settlement.
  - Cracking of embankment due to uneven settlement.
  - Excessive pore pressure in structure, foundation, or abutment.
  - Excessive loading due to buildup of silt load against dam.
  - Excessive leakage through foundation.
  - Embankment slope failure.
  - Leakage along conduit in embankment.
  - Channels from tree roots or burrowing.
  - Landslide in reservoir.
  - ……….

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6. Introduction (Cont.)

- The possibility of sunny day failures should be carefully evaluated to ensure that all plausible mechanisms for flooding from dam breaches and failures at and near a site are considered.
- Dams failed due to hydrologic and seismic events shown to have negligible impacts at the site do not require evaluation for the sunny-day scenario since the sunny-day scenario is bounded by the other two events.
- The level of effort required for evaluating sunny-day failure is typically lower since it only involves identifying the worst-case individual or cascading failure scenario.

6. Introduction (Cont.)

- Base flow conditions for a sunny day failure are typically ignored because of the small discharge and volume compared to that of a dam breach.
- Additional inflow (e.g. from a storm event) is not required when analyzing a sunny day breach.
- A sunny day breach can be used to model piping failures for hydrologic, geologic, structural, seismic, and human-influenced failure modes.

6.1.1 Concrete Dams

- Potential failure initiators common to all types of concrete dams.
  - plugging of drains (leading to increased uplift pressures),
  - gradual creep that reduces the shear strength on potential sliding surfaces, and
  - degradation of the concrete from alkali-aggregate reaction, freeze-thaw, or sulfate attack.
  - Weak lift joints within dams.
- For concrete gravity dams founded on rock, the leading cause of dam failures has been related to sliding on planes of weakness within the foundation, most typically weak clay or shale layers within sedimentary rock formations.
- For concrete gravity dams founded on alluvial soils, the leading cause of failure is piping or “blowout” of the soil material from beneath the dam.

6.1.2 Embankment Dams

- Most common sunny day failure modes for embankment dams are initiated by or heavily influenced by various seepage-related internal erosion phenomena.
  - Piping
  - Scour
  - Heave
- Phenomena discussed above may affect the embankment (including spillway walls), the foundation or both

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6.2.1 Probability of Sunny Day Failure Modes

- Sunny day failure may be excluded from further consideration if it can be shown by a dam specific engineering assessment that the probability of failure is $1x10^{-6}$ per year or less using current best practices.
- As of this writing, the methods discussed in the USBR Dam Safety Risk Analysis Best Practices Training Manual (USBR, 2011) are considered by the staff to represent current best practice.
- Staff expects risk results to be based on a thorough engineering analysis similar in scope and rigor to the comprehensive facility review process described in USBR (2011).

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6.2.2 Initial Water Surface Elevation

- To account for floods of long duration, which may result in higher than normal water levels for extended periods, the default initial water level used in breach analysis and flood routings for evaluation of sunny-day failure should be the higher of the maximum observed pool elevation or the maximum normal pool elevation.
- Other water levels may be used with justification (e.g., records showing that water levels above max normal poll are infrequent and of short duration).

7.1 Operational Failures

- Operational failures that may lead to uncontrolled releases and threaten to inundate the NPP site should be considered.
- Examples
  - Failure of a log boom allows reservoir debris to drift into and plug the spillway, leading to premature overtopping of the dam.
  - Gates fail to operate as intended causing premature overtopping of the dam.
  - Loss of access to operate key equipment during a flood leads to overtopping of the dam or other uncontrolled releases.
  - Loss of release capacity leads to overtopping of the dam.
  - Mechanical equipment failure due to changes in operation without a corresponding change in maintenance.
  - Overfilling off-stream storage leads to overtopping and failure of the dam.
  - Failure to detect hazardous flows or a breakdown in the communication process to get people out of harm’s way

7.2 Controlled Releases

- The potential for controlled releases that may threaten to inundate the NPP site should be considered.
- Examples:
  - Releases performed in order to prevent dam failure during flood conditions
  - Releases performed to rapidly drawdown a reservoir to prevent incipient failure after a seismic event
  - Releases performed to rapidly drawdown reservoir to prevent incipient sunny day failure.

8. Dam Breach Modeling

- 8.1 Breach Modeling for Concrete Dams
- 8.2 Breach Modeling of Embankment Dams
- 8.2.1 Regression Equations for Peak Outflow from Breach
- 8.2.2 Regression Equations for Breach Parameters
- 8.2.2.1 Uncertainty in Predicted Breach Parameters and Hydrographs
- 8.2.2.2 Performing Sensitivity Analyses to Select Final Breach Parameter
- 8.2.4 Physically-Based Combined Process Breach Models

8.1 Concrete Dam Breach

- Concrete gravity dams
  - Tend to have a partial breach as one or more monoliths sections formed during construction of the dam are forced apart and overturned by the escaping water
  - The time for breach formation depends on the number of monoliths that fail in succession, but is typically on the order of minutes
- Concrete arch dams
  - Tend to fail completely
  - Assumed to require only a few minutes for the breach formation.
  - Shape of the breach is usually approximated as a rectangle, or a trapezoid.
- Buttress and multi-arch dams
  - Sections are assumed to fail completely
  - Assumed to require only a few minutes for the breach formation.
  - Shape of the breach is usually approximated as a rectangle, or a trapezoid.

8.2 Embankment Dam Breach

- Overtopping Failure
  - Once a developing breach has been initiated, the discharging water will progressively erode the breach until either the reservoir water is depleted or the breach resists further erosion.
  - Erosion processes typically result in the progressive widening and deepening of the breach. In some cases, the breach will deepen until the bedrock foundation or some other erosion resistant strata is encountered. At this point, the breach depth stays approximately constant while the breach continues to widen.
  - The final breach shape is often modeled as trapezoidal.
- Piping Failure
  - Breach opening in the dam initially forms at some point below the top of the dam.
  - As erosion proceeds, the "pipe" through the dam enlarges until the top of the dam collapses, or the breach becomes large enough that open channel flow occurs.
  - Beyond this point, breach enlargement is similar to the overtopping case.

8.2.1 Regression Equations for Peak Outflow from Breach

- A number of regression equations have appeared in the literature in the past 35 years.
  - Some attempt to provide conservative estimates by developing equations that envelope the case study data, while others provide a best fit to the data.
- For screening-level analysis, use of simple equations that relate the peak outflow discharge to basic reservoir and embankment parameters is acceptable with adequate justification.
  - Selection of candidate methods should consider the assumptions inherent in the models and their applicability to the dam failure scenario being considered.
  - Sensitivity studies should be performed on a reasonable variation of input parameters, when applicable.
  - If there are multiple applicable models, a study should be performed to evaluate the effect of model selection (and input parameter sensitivity, when applicable) on the results of the analysis.
  - Justification for the chosen model and input parameters should be documented, including results of sensitivity studies.

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8.2.2 Regression Equations for Breach Parameters

- Regression equations have been developed to predict parameters of the breach opening (e.g., size, shape, and rate of development) when given input data such as reservoir volume, initial water height, dam height, dam type, configuration, failure mode, and material erodibility.
- Breach parameters are then used in a computational model that determines the breach outflow through the parameterized opening using a weir or orifice flow equation.
- A number of regression equations have appeared in the literature in the past 35 years.

8.2.2 Regression Equations for Breach Parameters

- The state of practice in dam breach modeling shows a clear preference for regression-based approaches.
- Preferred approach uses regression equations to predict final parameters of the breach opening (.e.g. size, shape, time to fully develop) when given input data such as reservoir volume, initial water height, dam height, dam type, failure mode, and material erodibility.
- Because of the large uncertainties, inconsistencies and potential biases discussed above, one should not rely on a single method/equation.
- Compare the results of several models judged to be appropriate. Provide justification for choice of candidate models and final parameter choices. Explicitly address model and parameter uncertainty as well as parameter sensitivity in final results.
- Failure time uncertainties can be quite large.
  - Observations of failure time in case studies generally originate from non-professional eyewitness; and
  - Lack of clear and consistent definition of failure time across (and sometimes within) studies.
- Need to understand how failure time is defined in the relations used and ensure that there is consistency with the way failure time will be used in the modeling of the breach formation process.

8.2.3 Physically-Based Combined Process Models

- The state of practice in dam breach modeling shows a clear preference for regression-based approaches
- Use of physically-based breach modeling will be considered on a case-by-case basis.
- If used, the parameters describing erosion and hydraulic properties should be developed from site-specific studies.
- Generic values or values obtained from the literature are, in general, not sufficient.
- Uncertainty and sensitivity studies should be performed to evaluate the effect of model and input parameter selection on the results of the analysis.
- Justification for the selected model and input parameters should be provided, including documentation of uncertainty and sensitivity studies.

9. Levee Breach Modeling

- In general, levees should be assumed to fail when overtopped.
  - The case for nonfailure must be developed using detailed engineering analysis supported by site-specific information, including material properties of the embankment and foundation soils, material properties of embankment protection (if any), levee condition, etc.
- Levees generally not designed to withstand high water levels for long periods. However, there is no generally accepted method for predicting how long a levee will continue to function under high loading conditions.
  - Historical information is the best available basis for predicting levee performance. The historical information should be from levees that have similar design and construction as the levee being analyzed.
- Since there is no widely accepted method for modeling breach development in the case of levees, conservative assumptions regarding the extent of the breach and the failure time should be used.
- In general, inundation mapping of the NPP site from an onsite or nearby levee will require two-dimensional modeling.

10. Flood Wave Routing

- 10.1 Applicability and Limitations of Hydrologic Routing Models
- 10.2 Hydraulic Models

10.1 Hydrologic Routing

- Commonly used Hydrologic methods
  - Muskingum
  - Modified Puls (also known as storage routing)
  - Muskingum Cunge
- Applicability and Limitations of Hydrologic Routing Models
  - Backwater Effects
  - Floodplain Storage
  - Interaction of Channel Slope and Hydrograph Characteristics
  - Configuration of Flow Networks
  - Occurrence of Subcritical and Supercritical Flow
  - Availability of Calibration Data Sets

10.2 Hydraulic Models

- Hydraulic routing provides more accuracy when modeling flood waves from dam breach because it includes terms that other methods neglect and therefore, it is not subject to the restrictions discussed for hydrologic models.
- Typically, a dynamic hydraulic model should generally be used to route the dam failure flood wave to the plant.
- For inundation mapping of the NPP site, two-dimensional models are generally preferred by the staff. However, use of one-dimensional models may be appropriate in some cases. Therefore use of one-dimensional models will be accepted on a case-by-case basis, with appropriate justification.
- Transport of sediment and debris by the flood waters should be considered.
- Large uncertainty exists in relationships between water elevation and discharge (rating curves), especially at high river discharges. Typically, observed data are extrapolated well beyond field-observed data when discussing dam breach scenarios. Some estimation of the likely variation in maximum water surface stage at the NPP site should be reported to account for this uncertainty in the rating curve.