VI-3. Cavitation Damage Induced Failure of Spillways

Key Concepts

Description of Potential Failure Mode

Cavitation is the formation of vapor cavities in a liquid. Cavitation occurs in high velocity flow, where the water pressure is reduced locally because of an irregularity in the flow surface. As the vapor cavities move into a zone of higher pressure, they collapse, sending out high pressure shock waves (see Figure VI-3-1). If the cavities collapse near a flow boundary, there will be damage to the material at the boundary. Cracks, offsets and surface roughness can increase the potential for cavitation damage. The extent of cavitation damage will be a function of the cavitation indices at key locations in the spillway chute and the duration of flow. This failure mode will typically only be a concern with spillway chutes, since cavitation damage in tunnels and conduits will be less likely to lead to dam failure due to the directivity of the flow and the confined location of the feature. This failure mode is unlikely to progress to the point where dam failure occurs in most cases, due to the long flow durations that are required to cause major damage to concrete linings.

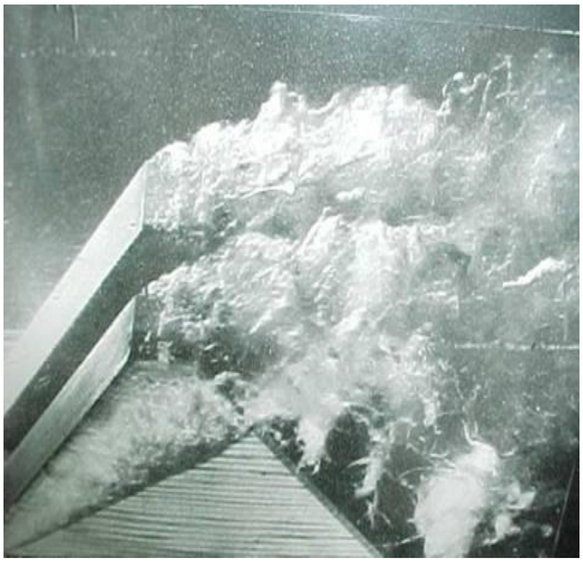


Figure VI-3-1 – Cavitation Created in Low Ambient Pressure Chamber

Condition of Concrete in Spillway

Cracks, offsets, surface irregularities and/or open joints in chute slabs (or tunnel linings) and the lower portions of chute walls exposed to flow, may allow this failure mode to initiate. The geometry of the flow surface irregularities will affect the initiation of cavitation. The more abrupt the irregularity, the more prone the spillway will be to the initiation of cavitation. Concrete deterioration in the form of alkali-silica reaction, freeze thaw damage and sulfate attack can exacerbate this potential failure mode due to the resulting cracks or opening of cracks and joints in the concrete, creating surface irregularities and/or offsets at damaged areas.

Cavitation Indices

Cavitation indices can be used to evaluate the potential for cavitation damage in a spillway chute or tunnel. The cavitation index is defined as follows:

$$\sigma = \frac{P - P_v}{\frac{\rho V^2}{2}}$$

where,

P = pressure at flow surface (atmospheric pressure + pressure related to flow depth)
P_v = vapor pressure of water
ρ = density of water
V = average flow velocity

There is the potential for cavitation damage when the cavitation index, σ is between 0.2 and 0.5, for typical concrete. For large features that are introduced into the flow abruptly (such as stilling basin baffle blocks or splitter walls), cavitation damage can occur when the σ is as high as 1.0 or greater.

Aeration of Flow

The introduction of air into spillway flows reduces the potential for cavitation to damage concrete surfaces. Aeration reduces the damage that occurs from collapsing vapor cavities. If the flow is not naturally aerated, measures can be taken to introduce air into the flow at critical locations along a spillway. Air vents on morning glory spillways or downstream of gates are not designed for cavitation mitigation.

Flood Routing Results/Flood Frequency

Routings of specific frequency floods provide discharges and durations for a flood with a given return period. This information can be used to generate probabilities for certain discharge levels.

Spillway Discharges (Velocities, Depths and Durations)

Water surface profiles can be calculated for discharges that are obtained from the routings of frequency floods. The water surface profiles can provide depths of flow, velocities and cavitation indices at selected stations along the spillway. If the cavitation indices are not calculated by the water surface profile program (which is an option with the water surface profile program ZPROF) cavitation indices can be calculated at any location along the spillway, where the depth and velocity of flow are known. The cavitation indices at offsets or irregularities along the spillway chute will help determine the potential for cavitation damage to initiate. Flood routings will provide information on the duration of certain discharge levels. If durations of spillway flows are limited, failure of the spillway chute or lining may initiate but there may not be time for a breach of the reservoir to develop.

Erodibility of Foundation Materials

Soil foundations are generally more erodible than rock foundations. If erosion of the foundation materials initiates and progresses, this could lead to undermining of the spillway foundation, collapse of the chute slab or lining, headcutting and upstream progression of erosion. The degree of erosion will be a function of the erodibilty of the foundation materials (see section on Erosion of Rock and Soil). If the foundation consists of competent rock, the potential for undermining erosion and upstream progression of erosion may be limited.

Spillway Configuration

Uncontrolled spillways cannot be regulated and provide little or no opportunity to reduce discharges to control flows should problems develop during flood releases. Gated spillways may allow the opportunity reduce flows (assuming that there is adequate surcharge space to allow this to happen without risking an overtopping failure of the dam) and slow down or arrest failure of the entire spillway if this failure mode is in progress. Short term gate closure may allow time to install temporary measures to mitigate this potential failure mode.

Event Tree

Figure VI-3-2 is an example of an event tree for this potential failure mode (only one branch shown completely). The event tree consists of a number of events that lead from initiation, through progression, to breach of the reservoir. The first node represents the starting reservoir water surface elevation range (prior to a significant flood) and the second node represents flood load ranges. The combination of these two nodes represents the combined load probability and determines the range of spillway discharges that apply to each branch. The remaining nodes in the event tree represent the conditional probability of failure given the load. The remaining nodes include the following: 3. Cavitation Damage Initiates (at a given flow); 4. Spillway Lining Fails; 5. Headcutting Initiates; 6. Unsuccessful Intervention; and, 7. Breach Forms. Since the flood load range probability is typically dominated by the lower end of the range, the failure probability should also be weighted toward the lower end of the range. Refer also to the section on Event Trees for other event tree considerations. With the tools currently available, the estimates for most nodes on the event tree must by necessity be subjective (see section on Subjective Probability and Expert Elicitation).

Flood Studies/Flood Routing Analyses/Water Surface Profiles

A flood frequency study, along with the development of frequency hydrographs is required to fully evaluate this potential failure mode. Flood hydrographs should include a range of floods from the point where spillway releases become significant up to the Probable Maximum Flood (PMF).

A flood routing study is then conducted in which the frequency floods are routed and spillway discharges and durations determined for each flood event. If the starting reservoir water surface elevation is likely to vary (based on historical reservoir elevations), and the initial reservoir elevation has a pronounced effect on the results, the routings should be performed with a number of different starting reservoir water surface elevations.

Water surface profiles are then generated, using spillway discharge information from the frequency flood routings. For a given discharge, flow depths, velocities and cavitation indices can be determined at key stations along the spillway. The water surface profile program (ZPROF) calculates cavitation indices at identified stations along the spillway, in addition to providing the flow depth and velocity at those stations. This information along with information on offsets and irregularities on the spillway flow surface can be used to estimate probabilities for the development of this potential failure mode.

Spillway Inspections

It is generally better to inspect the spillway flow surface for joints, cracks and irregularities prior to assessing the risk. Locations where these features exist, particularly abrupt changes in the flow surface, should be noted so that flows at those locations can be studied in detail. However, it is not always practical to inspect a spillway, particularly for a screening level analysis. When available, design and construction details can be studied. When a spillway is suspected of having unfavorable conditions, it may be reasonable to estimate the risks assuming both favorable and unfavorable conditions. The difference in risks may provide justification to verify the condition of the spillway flow surface.

When a spillway is inspected, the inspection team should have knowledge of the design and construction. This will help in identifying areas where unfavorable conditions exist. For example, if the spillway chute joints are not keyed and do not have continuous reinforcement across the joints, there may be the potential for offsets to be created at joints. Delamination is not always apparent during a visual inspection. A delaminated surface may be eroded during high flows, creating irregularities that could initiate cavitation. Heave or settlement of the spillway chute slabs or flow surface may produce offsets that are difficult to detect. Rapping the concrete surface with a hammer or other object may produce a hollow sound, indicating perhaps delamination or voids related to differential settlement exist.

A detailed inspection of the spillway will likely result in specific areas of concern related to cavitation potential. These areas may get special attention during the failure mode analysis. However, other areas should be included in the analysis because the likelihood of failure in those areas may be higher depending on the cavitation indices. Periodic inspections should focus attention on areas where the risk resulting from surface irregularities is greatest.

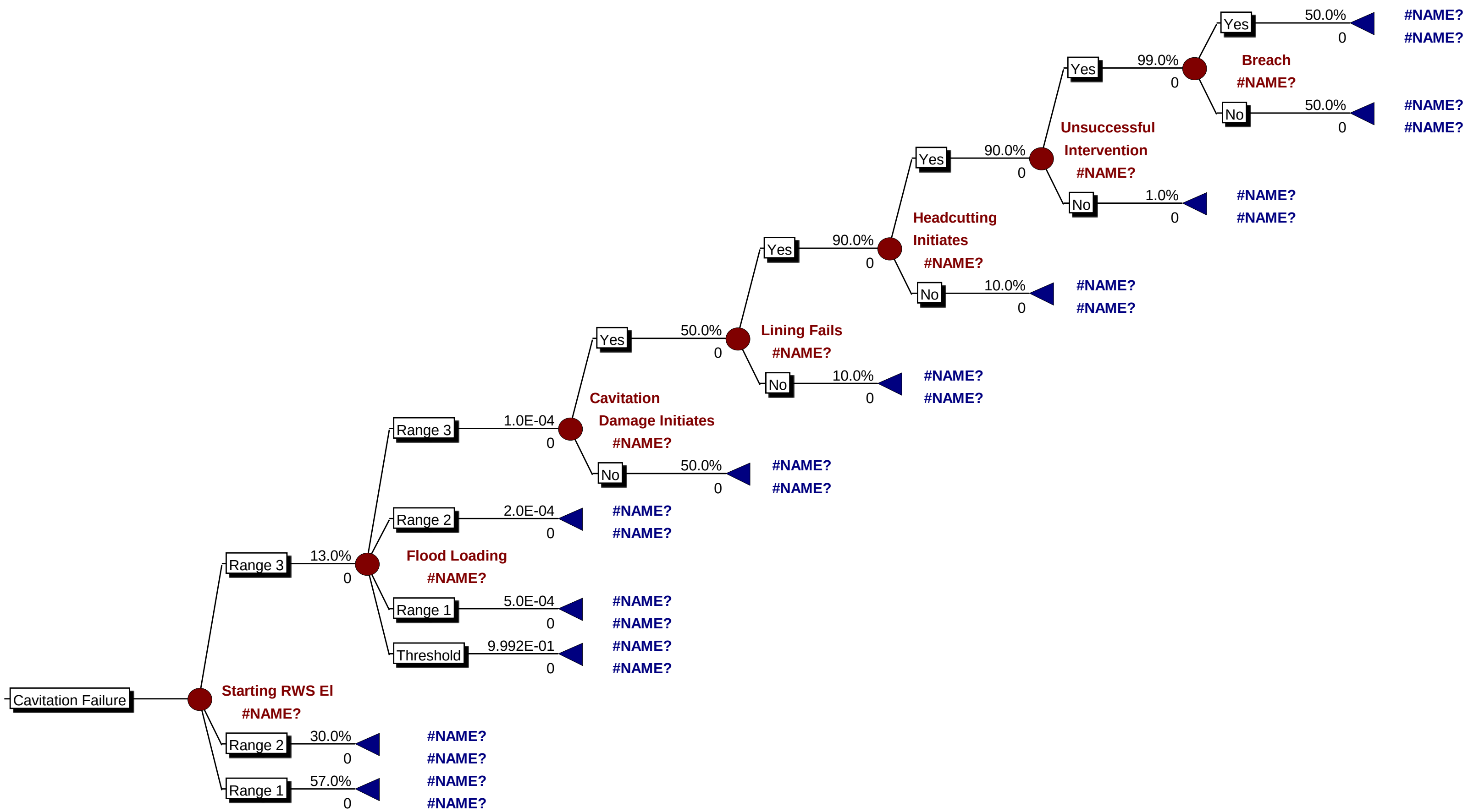


Figure VI-3-2 - Example Event Tree

Starting Reservoir Water Surface Elevation

Starting reservoir water surface elevation ranges are used as nodes in the event tree if varying this parameter made a significant difference in the flood routing results. If this parameter is significant, the reservoir load ranges are typically chosen to represent a reasonable breakdown of the larger reservoir range from the normal water surface to an elevation representing the lower limit of what would typically occur before a major flood. This would typically result in several (perhaps3 to 4 reservoir load ranges). Historical reservoir elevation data can be used to generate the probability of the reservoir being within the chosen reservoir ranges, as described in the section on Reservoir Level Exceedance Curves.

Flood Load Ranges

Flood load ranges are typically chosen to provide a reasonable breakdown of the flood loads from the maximum flood routed (with the Probable Maximum Flood (PMF) representing the maximum flood that would be considered) to a threshold flood where the spillway discharges are at a level below which failure due to cavitation is judged to be remote. This would typically result in several (maybe 3 to 6 flood load ranges). Flood frequency curves (or hydrologic hazard curves) are used to generate the probability distributions for the flood load ranges, as described in the section on Hydrologic Hazard Analysis.

Cavitation Damage Initiates

The initiation of cavitation damage requires irregularities along the flow surface and a low cavitation index associated with a spillway flow. Cavitation is typically initiated by singular isolated irregularities or roughnesses along a flow surface. Typical examples of irregularities in hydraulic structure flow surfaces include the following:

- Offsets into the flow.
- Offsets away from the flow.
- Holes or grooves in the flow surface.
- Protruding joints.
- Calcite deposits on the flow surface.

For all of these occurrences, cavitation is formed by turbulence in the shear zone (interface between high velocity and low velocity flow); which is produced by the sudden change in flow direction at the irregularity. The location of the shear zone can be predicted by the shape of the roughness. Depending on the shape of the roughness, cavitation bubbles will collapse either within the flow or near the flow boundary. If a recent, thorough examination of the spillway has been performed, surface irregularities can be identified. If a recent examination has not been performed, it may be reasonable to evaluate the risk assuming both favorable and unfavorable conditions. The difference in risk between these two conditions may provide justification for further characterization of the flow surface.

If multiple surface irregularities exist along a spillway chute, it may be desirable to consider several locations separately. It is possible that a location that is more likely to initiate cavitation damage may be more resistant to the full development of a reservoir breach (due to more resistant foundation materials or a longer distance from the reservoir).

After flow rates are determined for various flood frequencies, water surface profiles can be developed to determine flow depth and velocity at locations along a spillway chute or tunnel. This information can be used to calculate cavitation indices at key locations along the chute/tunnel. These key locations would include any areas where surface irregularities or offsets have been identified or where it is expected that these features might exist. Lower cavitation indices indicate a higher potential for cavitation damage. The cavitation index will decrease with an increase in flow velocity and a decrease in the pressure at the flow surface. For a given flow, there may be portions of the spillway that are vulnerable to the initiation of cavitation, while other portions may not be vulnerable. As flows increase, additional portions of the spillway may experience conditions that can initiate damage. Therefore, there may be a specific flow for different sections of a spillway that will represent an initiating failure condition.

Cavitation occurs in several phases. Incipient cavitation occurs when occasional cavitation bubbles develop in the flow. Developed cavitation occurs when many small cavitation bubbles are formed, appearing as a fuzzy white cloud. Supercavitation occurs when large vapor cavities are formed from individual cavitation bubbles.

The rate of cavitation damage is not constant with time. At first, a period begins where loss of material does not occur. This period is known as the incubation period. In this phase surfaces become pitted. Following the incubation period, the damage rate increases rapidly during a period called the "accumulation period." The damage rate reaches a peak during this period. The last phase is an attenuation phase in which the damage rate decreases. (However, if the damage has resulted in loss of the concrete spillway lining, large turbulence and erosion can occur, which is evaluated at a later node.)

The initiation of cavitation damage can be predicted by the cavitation index of the flow. In general, if the cavitation index is greater than 0.5, significant damage is not expected for a typical spillway chute or tunnel lining. For cavitation indices between 0.5 and 0.2, damage can occur if surface irregularities exist. If the irregularity is large and abruptly introduced into the flow, such as a stilling basin baffle block or a stilling basin splitter wall, damage may occur for flow with a cavitation index of 1.0 or even greater than 1.0. For flow surface irregularities that are abrupt but small (such as offsets at joints, or localized spalled areas with a steep profile), damage may initiate during flow with a cavitation index as high as 0.5. If the irregularity is more gradual, the cavitation index may have to approach 0.2 in order for damage to occur. If the cavitation index is below 0.2, air entrainment is the only reliable method of preventing cavitation damage.

Whether cavitation initiates or not will be a function of the cavitation index of the flow and the geometry of the surface irregularity that potentially could initiate cavitation. Figures VI-3-3 and VI-3-4 provide information on incipient cavitation for chamfers and for isolated surface irregularities. Incipient cavitation is the stage at which occasional cavitation bubbles form in the flow. Damage is not expected at this level of cavitation – the cavitation index must drop significantly for cavitation to progress and for damage to initiate. For hydraulic structures, damage has been experienced at flow cavitation indices that are one-sixth to one-fourth of the incipient cavitation values (Falvey, April 1990).

Additional graphs are included in Chapter 2 of Reclamation's Engineering Monograph No. 42 (Falvey, April 1990) that provide incipient cavitation characteristics for a wide range of surface irregularities.

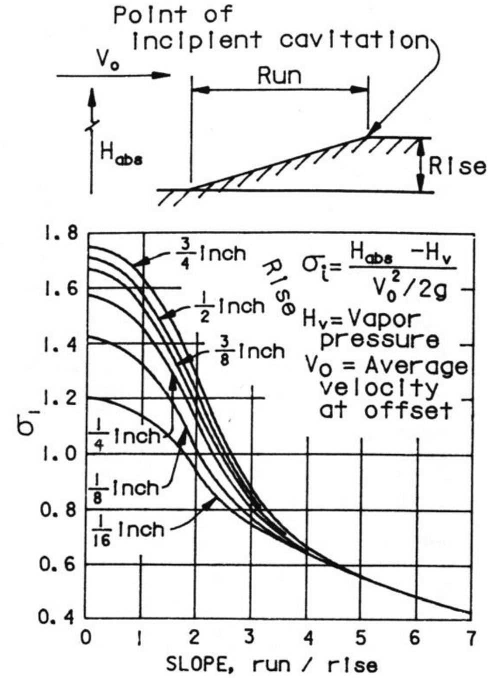
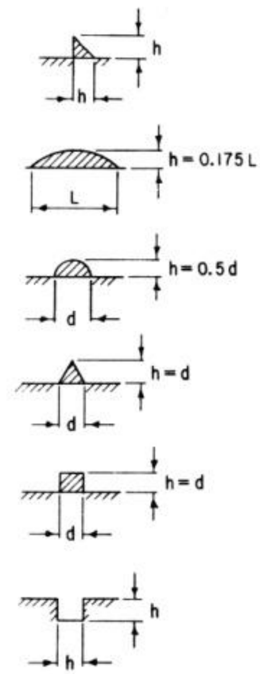


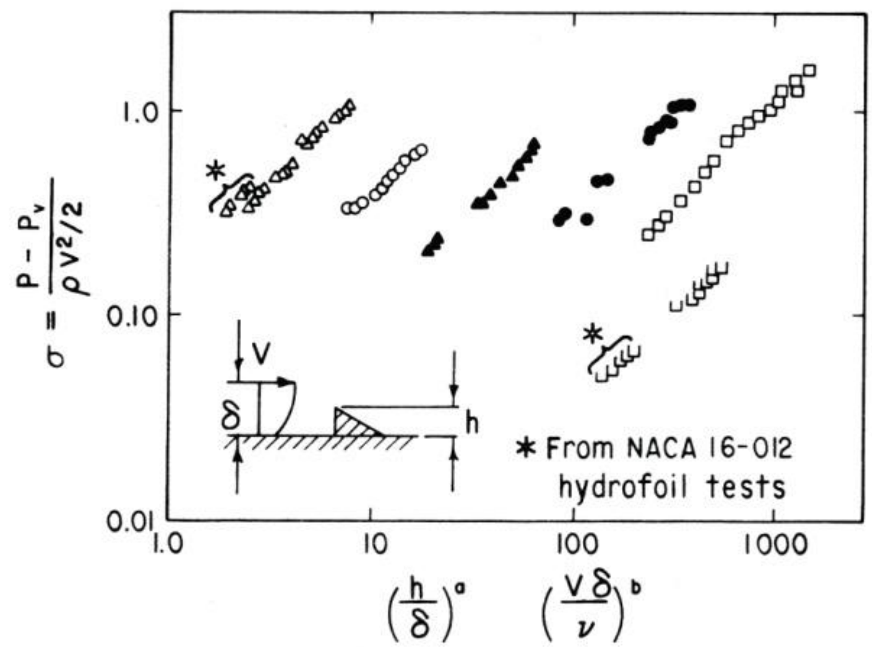
Figure VI-3-3 – Incipient Cavitation Characteristics of Chamfered Offsets (from Falvey (1980))

Aeration of spillway flows may prevent cavitation damage from initiating. When flow is only minimally aerated, damage has been found to vary inversely with the air concentration. This conclusion was reached based on tests conducted with air concentrations between 8 x 10^{-6} and 20 x 10^{-6} moles of air per moles of water (Stinebring, 1976). At high air concentrations of about 0.07 moles of air per moles of water, damage was found to be completely eliminated over a 2-hour test period (Peterka, 1953).

There are two theories that explain why aeration reduces the potential for cavitation damage. One theory is based on the presence of non-condensable gases in the vapor pocket that cushion or retard the collapse process. This theory is questionable, since studies have indicated that the diffusion of undissolved gases into a vapor cavity proceeds at a very slow rate relative to the rate of vaporization. Because vapor cavities develop rapidly, it seems unlikely that sufficient gas would be present (in the vapor cavity) to significantly affect the rate of collapse of the cavity or the pressures generated by the collapse. The second theory is based on the reduction of the sonic velocity of the fluid surrounding the collapsing vapor bubble, due to the presence of undissolved air. The reduced sonic velocity of the surrounding fluid reduces the pressure intensity of the collapsing vapor bubble.

Symbol	Irregularity	Flow dimensions	Data source	a	b	c
△	Triangles	2	Holl, 1960	0.361	0.196	0.152
○	Circular arcs	2	Holl, 1960	0.344	0.267	0.041
▲	Hemispheres	3	Benson, 1966	0.439	0.298	0.0108
●	Cones	3	Benson, 1966	0.632	0.451	0.00328
■	Cylinders	3	Benson, 1966	0.737	0.550	0.00117
⊔	Slots (Grooves)	2	Bohn, 1972	0.041	0.510	0.000314





δ = boundary layer thickness = $0.38\ X_b/R_x^{0.2}$
X_b = distance from start of boundary layer
R_x = Reynolds number
V = velocity at top of boundary layer
ν = kinematic viscosity of water

Figure VI-3-4 – Incipient Cavitation Characteristics of Isolated Irregularities (from Falvey (1980))

Flows in spillways can be self-aerating when the turbulent boundary layer from the floor intersects the water surface. Air entrainment can also be generated by the boundary layer on the side walls of spillway chutes and downstream of piers on overflow spillways. The latter case is the result of flow rolling over on itself as it expands after passing through the opening between piers (Falvey, December 1980). Tools to evaluate the air concentration in spillway flows from natural aeration are not readily available. If an air slot or ramp has been designed to introduce air into spillway flows, air entrainment is likely downstream of the slot or ramp. Model study results or actual field testing of the air slot/air ramp can be used to estimate the downstream effectiveness of the air entrainment. If spillway flows are being considered that exceed the design capacity of the air slot or air ramp, the design should be evaluated to determine if the feature will perform as intended at higher flows. If air has not been intentionally introduced into the flow, it should be assumed that the flow is not aerated.

Spillway Lining Fails

Several mechanisms are usually involved in the damage of hydraulic structures due to cavitation. When cavitation forms in a concrete chute or lining due to a surface irregularity, surface damage will begin at the downstream end of the cloud of collapsing cavitation bubbles. After a period of time, an elongated hole will form in the concrete surface. The hole will get longer as high velocity flow impinges on the downstream end of the hole. This flow creates high pressures in microfractures in the concrete, formed around individual pieces of aggregate or within temperature cracks that developed during the concrete curing process. This creates pressure differentials between the impact zone and the surrounding area, which can cause aggregate or even chunks of concrete to be broken from the surface and swept away in the flow. As erosion from the high velocity flow continues, reinforcing bars become exposed. The bars may begin to vibrate, which can lead to mechanical damage of the surface and fatigue failure of the reinforcing bars.

If flow velocities are sustained for a long enough period, the concrete chute lining can be completed removed over a portion of the chute, exposing the underlying foundation. Figure VI-3-5 (Falvey, April 1980) depicts cavitation damage that has occurred in various spillways, as a function of the cavitation index and the duration of spillway discharges.

Headcutting Initiates

If the spillway concrete lining fails, foundation erosion initiating at the failed chute section could lead to headcutting upstream to the reservoir. This would be a progressive failure. As the first section of spillway fails, it exposes the foundation to full spillway flow. Foundation erosion is dependent on the erosion rate of the foundation and the duration of the flow. In general, rock foundations may take longer and require higher energy flows to erode significant amounts of material than soil foundations. Soil and rock properties play an important role in the erosion rate (see section on Erosion of Rock and Soil). The duration of the flood producing erosive flows is also a key factor.

This node will be more difficult to achieve for a tunnel. This is because a tunnel typically would be founded on rock which should have some erosion resistance. Also the structural configuration of the tunnel, consisting of a circular or semi-circular section will make it difficult to undermine and fail a cantilevered section of tunnel. If the location at which the lining fails is close to the wall of the abutment, it is possible that lateral erosion could cause a blowout of the abutment.

Unsuccessful Intervention

Once this failure mode initiates, successful intervention would prevent the failure mode from fully developing into a reservoir breach. One obvious form of intervention for a gated spillway is to close the gates. While this may prevent failure of the spillway, it could lead to other problems such as high reservoir loading on the dam or even dam overtopping. Therefore, closing gates may not be a practical solution for large floods, but may be possible for smaller floods that can be stored in the reservoir, or may be possible temporarily until other actions can be taken. Other forms of intervention that may be possible include diverting flows away from the failed section of the spillway, armoring the failed spillway section, using an emergency spillway or outlet, or constructing a temporary spillway in a benign saddle or other area.

Breach Forms

Assuming that headcutting initiates, it could progress upstream to the reservoir. The duration of the flood flows may be critical to formation of a full reservoir breach. If the spillway foundation is somewhat erosion resistant, the headcutting may not reach the reservoir before the flood is over. In highly erodible foundations, the reservoir may be breached a short time after the headcutting is initiated. Some spillway crest structures may be founded on rock, or have cutoffs to rock. This would delay failure of the crest. Deep cutoffs beneath the chute may also prolong the breach process. Spillways adjacent to embankment dams may carry the added threat of erosion to the embankment leading to a breach once the chute walls fail.

If a tunnel experiences failure of the lining, there can be progression of the failure to dam breach. Although probably unlikely, failure of the lining and erosion of the underlying foundation could lead to headcutting and ultimately breach of the reservoir through the spillway crest structure area. If a headcutting breach doesn’t occur, it’s possible that a blow out of the abutment, initiated by lateral erosion in a situation where there is a limited thickness of foundation rock between the tunnel and the wall of the abutment. In tunnels that had been used for construction diversion is it possible for erosion to fail the diversion plug and result in uncontrolled reservoir loss through the diversion inlet.

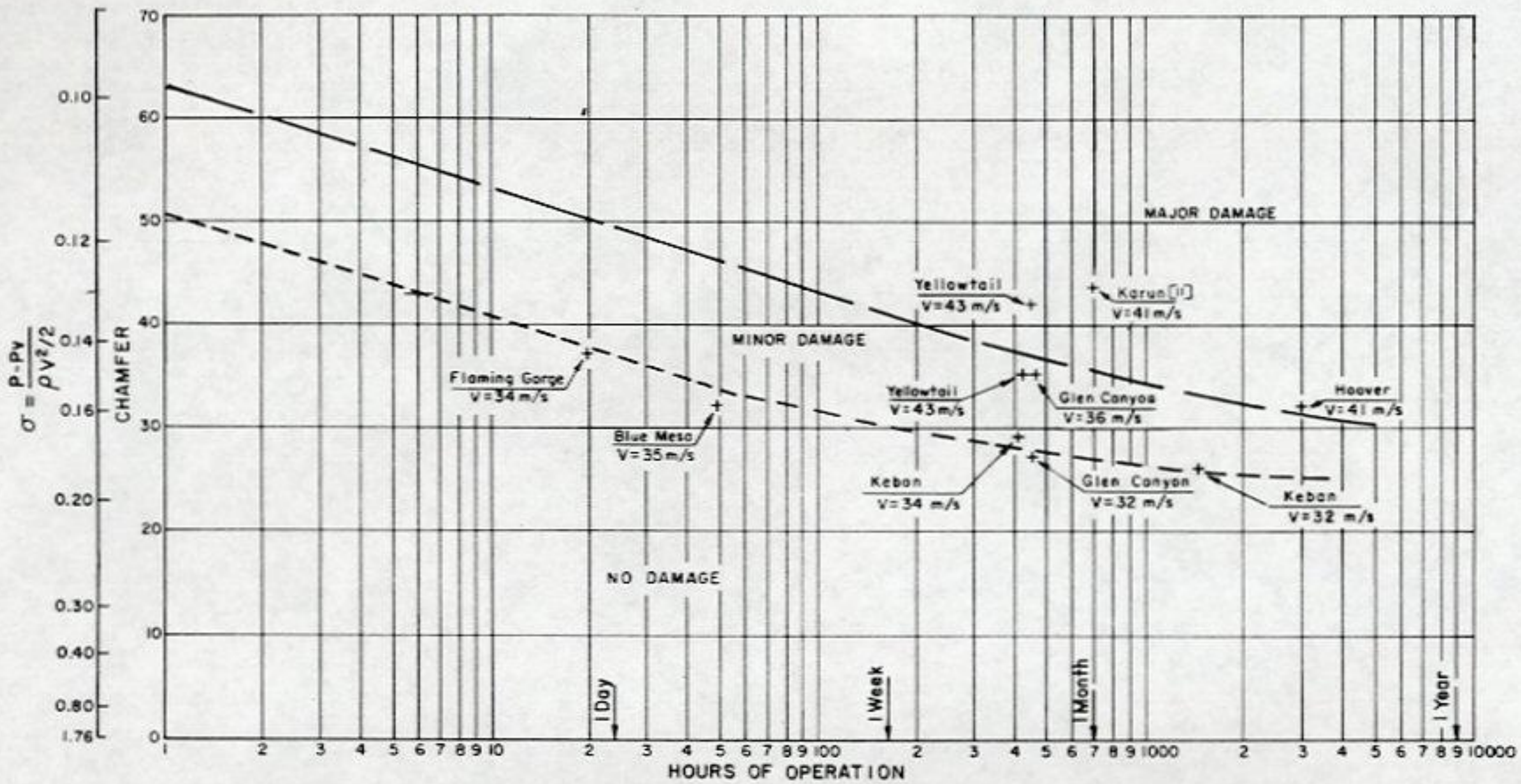


FIGURE 3-8.—*Damage experience in spillways (Falvey [9]).*

Cavitation in Chutes and Spillways

Figure VI-3-5 - Cavitation Damage as a Function of Cavitation Index and Hours of Operation (from Falvey (1980))

Consequences

Loss of life for the cavitation failure mode can be estimated from the predicted breach flows and the estimated population at risk that would be exposed to the breach outflows using the procedures outlined in the section on Consequences of Dam Failure. Incremental loss of life should be considered, which accounts for the fact that large spillway releases that may precede a breach of the reservoir through the spillway area, or in some cases a breach of the dam, may inundate significant portions of the downstream population, and may force their evacuation prior to dam failure, effectively reducing the population at risk (provided they evacuate to an area outside the breach inundation zone). Large spillway releases will also create a heightened awareness for populations located along the river channel and improve the chances for successful evacuation. Additionally, during a spillway release, the dam is likely to be under continuous surveillance, which should lead to early detection of this failure mode if it initiates and progresses. The failure mode will take some time to fully develop into a breach of the reservoir and early detection will provide for significant warning time. The SOP should be reviewed to determine the inspection requirements for the spillway during a flood event.

Accounting for Uncertainty

The method of accounting for uncertainty in the flood loading is described in the sections on Hydrologic Hazard Analysis and Event Trees. Typically, the reservoir elevation exceedence probabilities are taken directly from the historical reservoir operations data, directly, which do not account for uncertainty. Uncertainty in the failure probability and consequences are accounted for by entering the estimates as distributions (as describe above) rather than single point values. A "Monte-Carlo" simulation is then run to display the uncertainty in the estimates, as described in the section on Combining and Portraying Risks.

There may be some uncertainty regarding spillway discharges for a given frequency flood, because of unpredictability in how the spillway will actually operate during a flood event. Spillway capacity may be limited due to debris plugging or malfunctioning of spillway gates during a flood event, which would reduce the spillway discharge for a given frequency flood. It is not recommended that concerns over reduced spillway capacity be considered for this failure mode, since in most cases the probability of these reductions are low and they are difficult to quantify and including spillway plugging would reduce the likelihood of a cavitation-related failure.

There may be considerable uncertainty regarding the condition of the spillway chute, including whether surface irregularities, offsets, locally damaged areas or open joints or cracks exist in the spillway chute (due to lack of a recent thorough examination of the chute concrete). These uncertainties need to be considered and incorporated into the risk analysis estimates. Where conditions are unknown and the assumptions are critical (such as whether offsets exist at joints), risk estimates can be made for favorable and unfavorable conditions, and the results evaluated. The difference in the two estimates may provide justification to initiate an inspection program. If drawings are not available that provide design details for a spillway being evaluated (which will provide insight into the potential for irregularities on flow surfaces) the period in which the structure was designed and constructed can be used to make assumptions on which design features are likely, based on current practices at the time.

Relevant Case Histories

Glen Canyon Dam Spillway: June 1983

Glen Canyon Dam is located on the Colorado River in northern Arizona, about 15 river miles upstream of Lees Ferry and 12 river miles downstream from the Arizona-Utah state-line. The dam, completed in 1964, is a constant radius, thick-arch concrete structure, with a structural height of 710 feet. Spillways are located at each abutment and each consists of a gated intake structure, regulated by two 40- by 52.5 radial gates, a 41-foot diameter concrete lined tunnel through the soft sandstone abutments and a deflector bucket at the downstream end. Each spillway tunnel is inclined at 55 degrees, with a vertical bend and a 1000-foot long horizontal section. The combined discharge capacity of the spillways is 276,000 ft^3/s, at a reservoir water surface 63 feet above the spillway crest elevation. The spillways experienced significant cavitation damage during operation in June and July, 1993 during flooding on the Colorado River system when the reservoir filled completely for the first time and releases were required. The cavitation damage was initiated by offsets formed by calcite deposits on the tunnel invert at the upstream end of the elbow. Both spillways were operated at discharges up to about 30,000 ft^3/s. Cavitation indices of the flow in the area where damage initiated in the left spillway ranged from about 0.13 to 0.14. The cavitation indices of the deposits along the tunnel (indices at which cavitation was likely to occur) ranged from 0.64 to 0.73. Although flashboards were installed on top of the spillway gates to avoid releases to the extent possible, releases were still made through both spillways. The worst damage occurred in the left tunnel spillway – a hole 35-feet deep, 134-feet long and 50-feet wide was eroded at the elbow into the soft sandstone (Burgi, 1987). Extensive concrete repair work and installation of air slots was required to bring the spillways back into service and reduce the potential for future damage.

Exercise

Consider a spillway with a concrete lined chute. The chute slab is 12 inches thick (measured normal to the slope) and is founded on a hard rock foundation. Artificial aeration of the flow has not been provided and the flow in most of the chute in only minimally aerated. The foundation rock is heavily jointed and fractured. A recent inspection revealed that the spillway concrete is in excellent condition with the exception of a transverse joint at Station 17+04. Due to freeze-thaw action, the slab downstream of this joint has lifted off the foundation and a ½-inch offset into the flow has been created across most of the chute width. The information in Table VI-3-1 was extracted from a water surface profile study:

Table VI-3-1 – Flow Velocities and Cavitation Indices at Spillway Station 17+04			
Frequency Flood, yr	Spillway Discharge, ft^3/s*	Flow Velocity, ft/s	Cavitation Index
1000	2000	40	1.03
10,000	7300	55	0.50
100,000	17,800	88	0.31
1,000,000	25,300	91	0.20

* Spillway discharges did not change appreciably with a variable starting water surface elevation.

Estimate the expected annual probability for initiation of cavitation damage. Assume that the flows identified in the table are maintained for an extended period of time.

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