

# Cavitation Damage

Best Practices in Dam and Levee Safety Risk Analysis

Part F – Hydraulic Structures

Chapter F-3

Last modified June 2017, presented July 2019



US Army Corps  
of Engineers®



# Outline

- Cavitation Basics
- Case Histories
- Typical Event Trees
- Key Considerations
- Analytical Methods
- Defensive Measures



# Objectives

- Understand the mechanisms that cause Cavitation Damage
- Understand how to construct an event tree to evaluate the potential for major cavitation damage related failure
- Understand how to estimate potential for major cavitation damage and understand the progression mechanism to failure



# Key Concepts

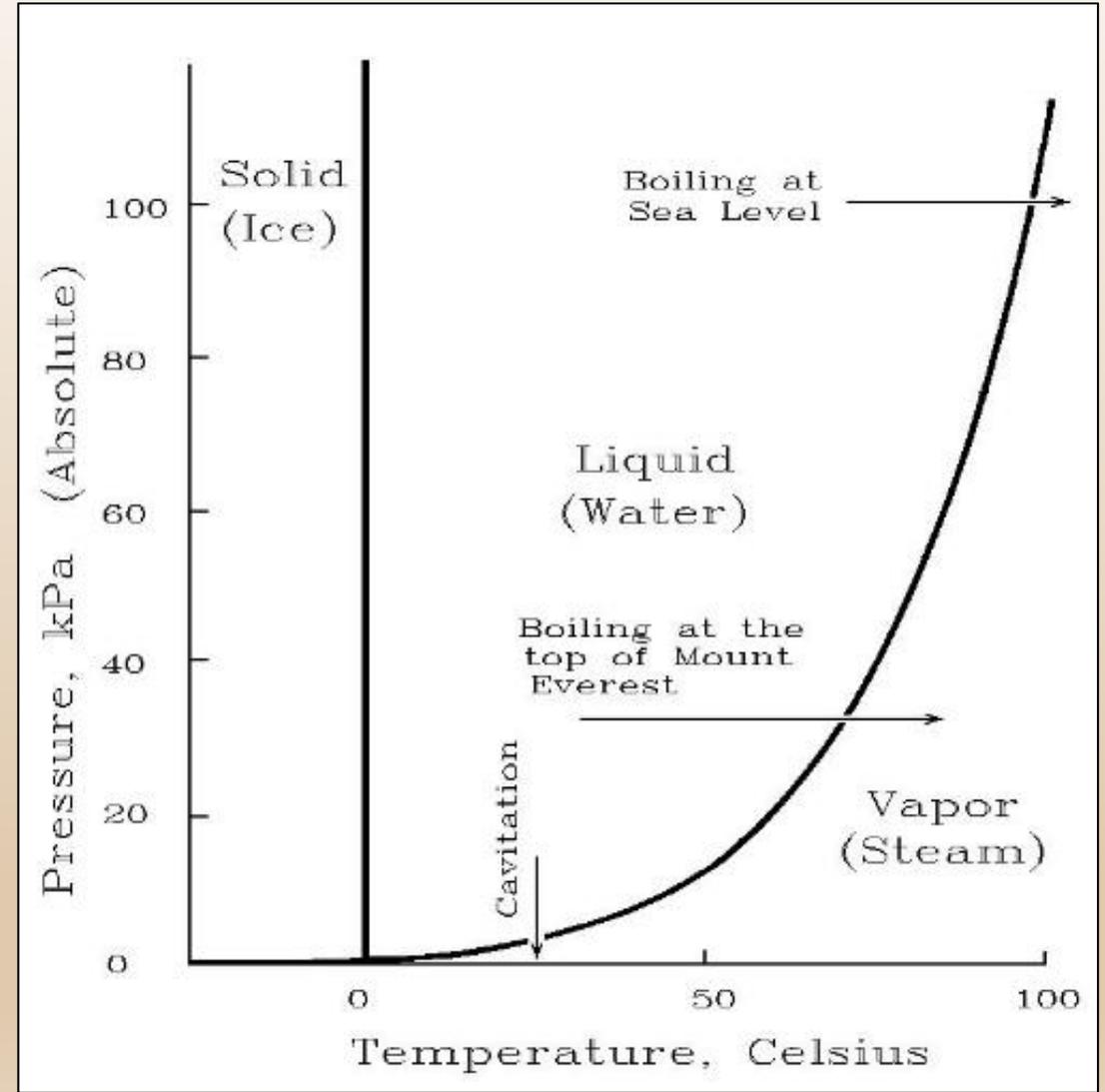
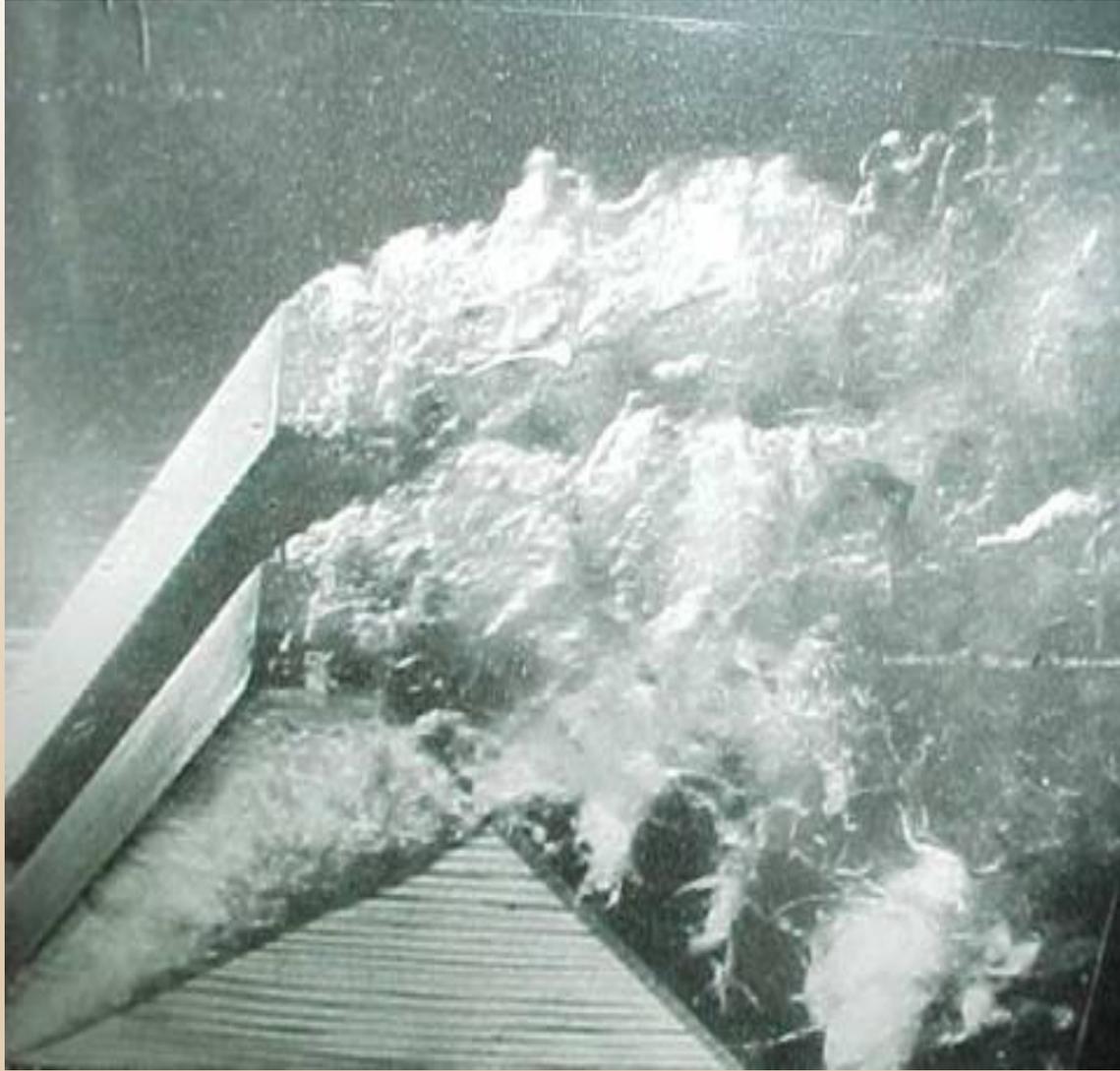
- Cavitation damage is a time dependent process
- Cavitation potential can be estimated by computing a cavitation index
- Cavitation damage potential is dependent on other factors including the air concentration in flow, the durability of materials, irregularities along the flow surface, and flow durations
- Cavitation damage has resulted in significant damage at several large federal dams



# Cavitation Basics

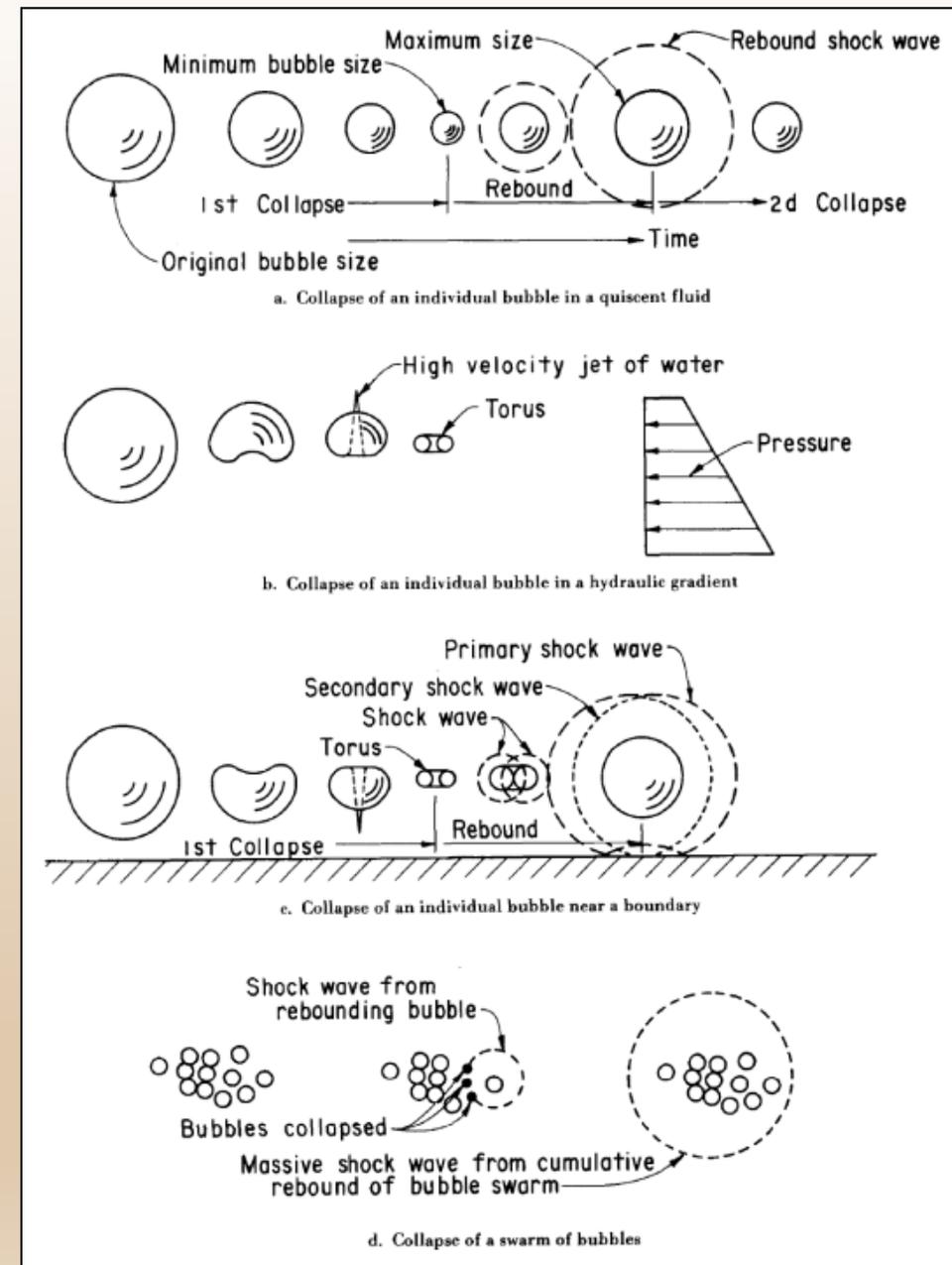


# Cavitation Basics



# Cavitation Basics

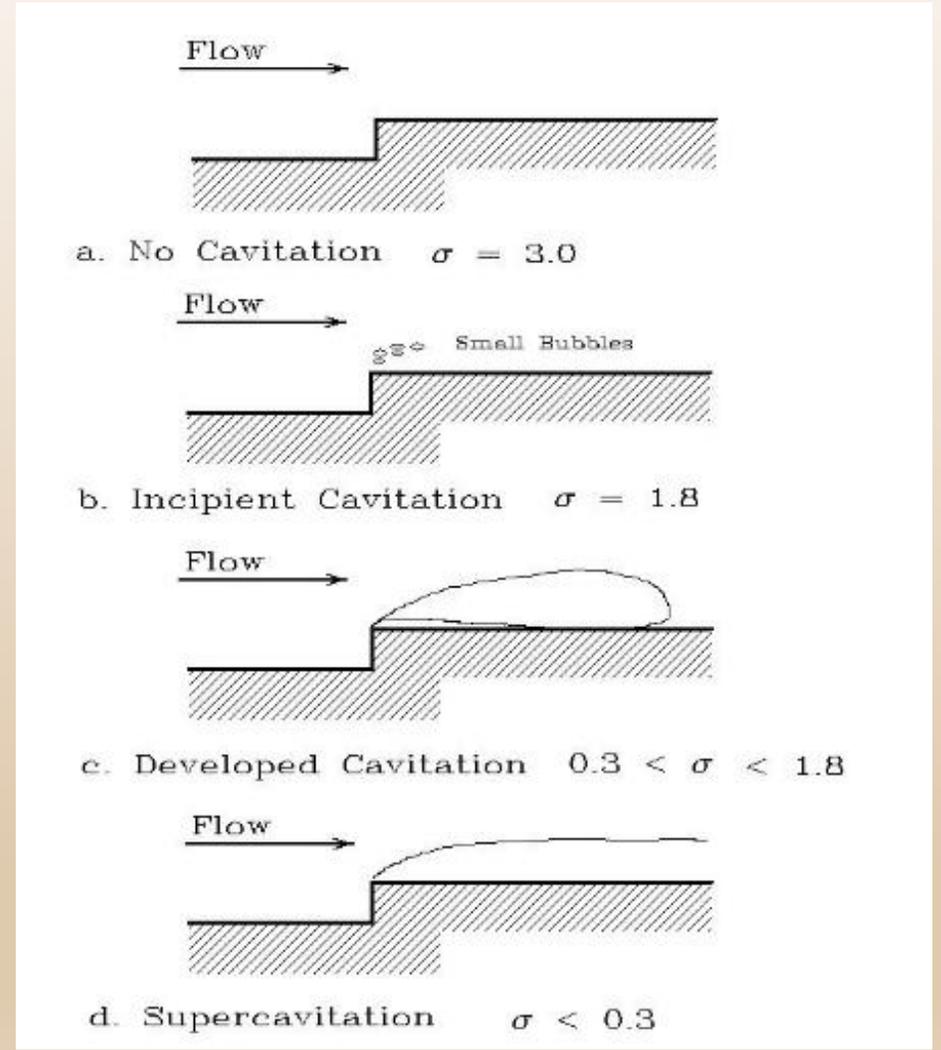
- Cavitation occurs in high velocity flow, where water pressure is reduced locally because of an irregularity in the flow surface
- As vapor cavities move into a zone of higher pressure, they collapse, sending out high pressure shock waves
- If the cavities collapse near a flow boundary, there will be damage to the material at the boundary (cyclical loading induced fatigue failure - - - Long duration)



# Cavitation Basics

## Phases of Cavitation

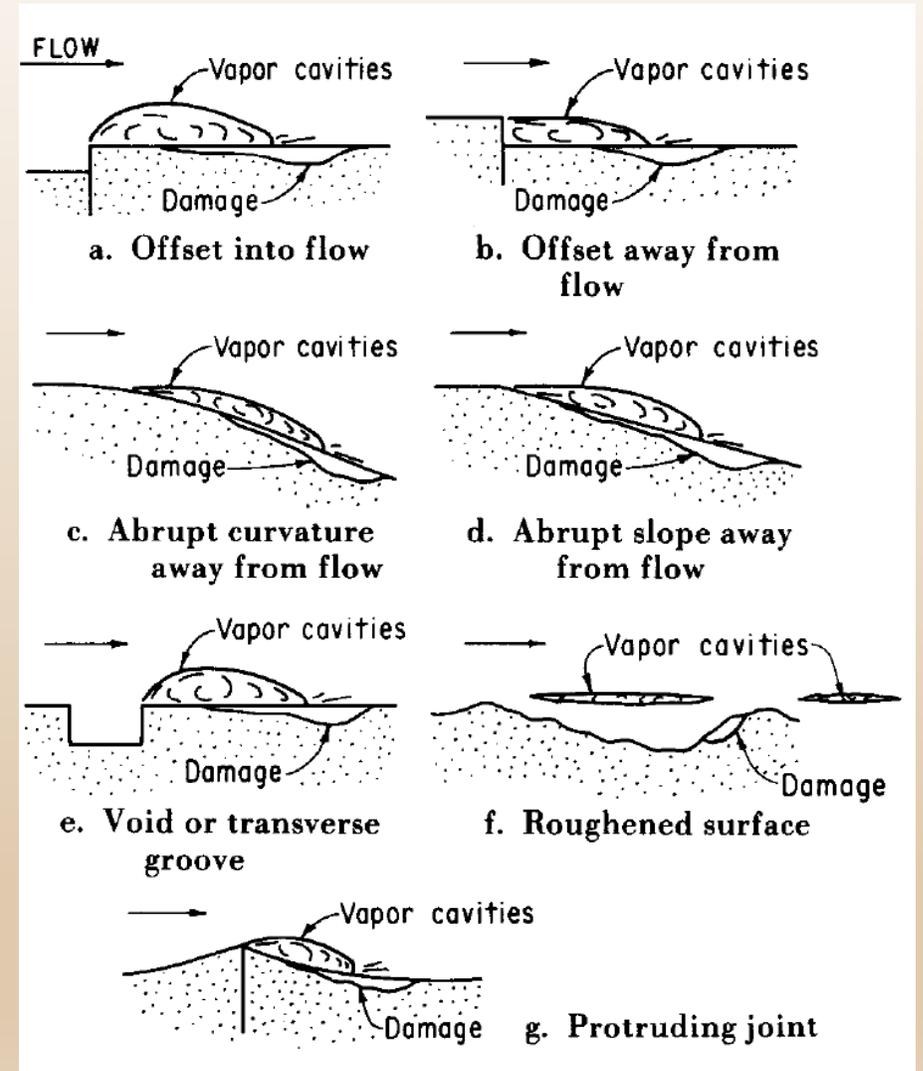
- Incipient Cavitation – occasional cavitation bubbles form in flow; damage typically occurs for cavitation index values one-sixth to one-fourth of the incipient cavitation index for a given surface irregularity
- Developed Cavitation – many small cavitation bubbles are formed, appearing as a white fuzzy cloud
- Supercavitation – large vapor cavities are formed from individual cavitation bubbles



# Cavitation Basics

## Cavitation Damage

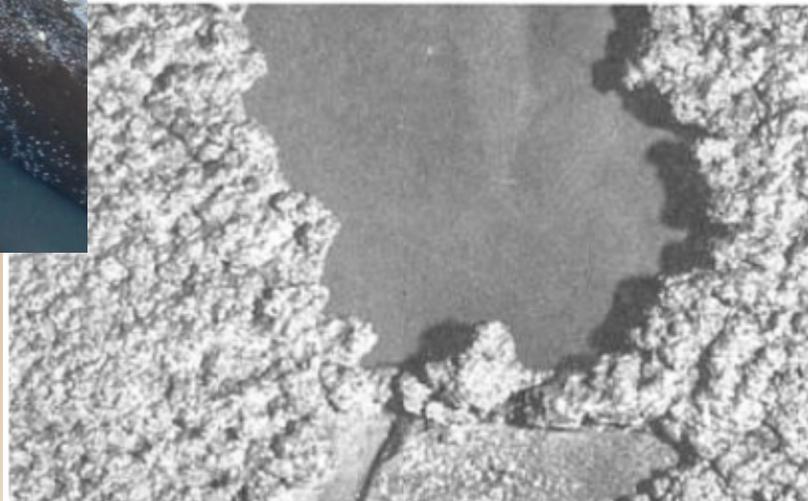
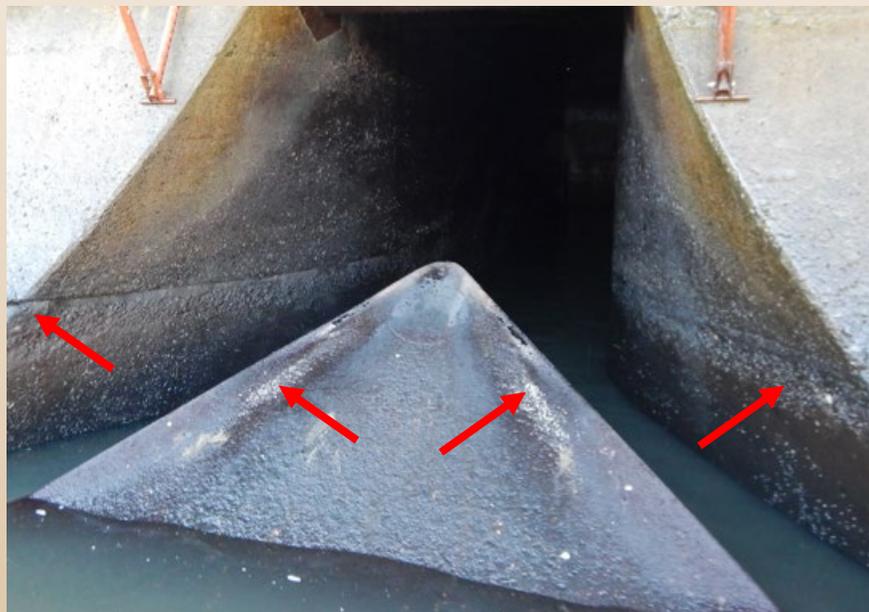
- Cavitation damage happens downstream from cavitation source (sudden change in pressure)
- Cavitation damage potential can be determined based on flow cavitation indices and the characteristics of flow surface irregularities
- Cavitation damage is a time dependent process



# Cavitation Basics

Spotting the Problem!

**NOT CAVITATION  
Damage**



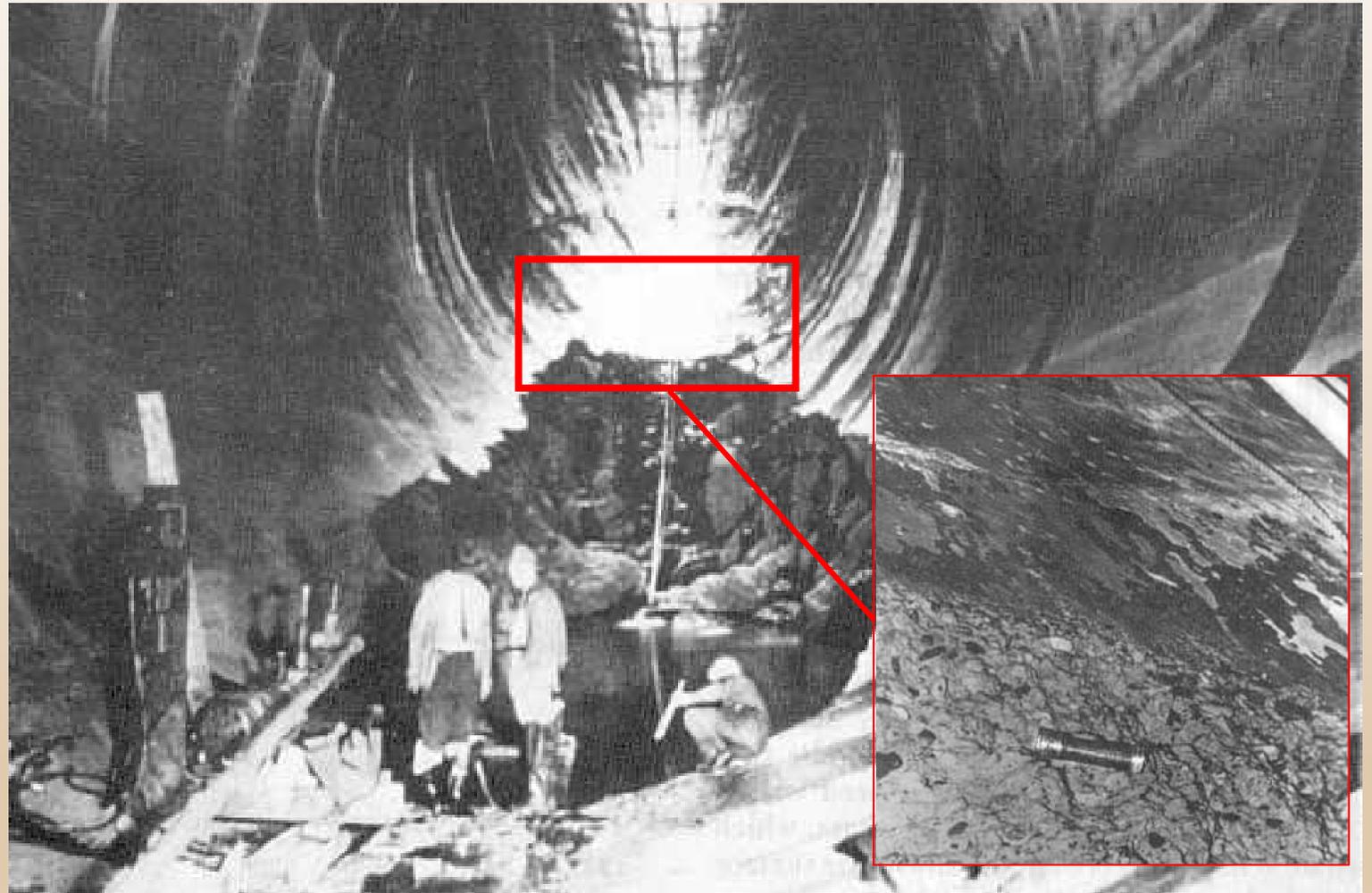
b. Ross Dam (Seattle, Washington) outlet works conduit

# Case Histories



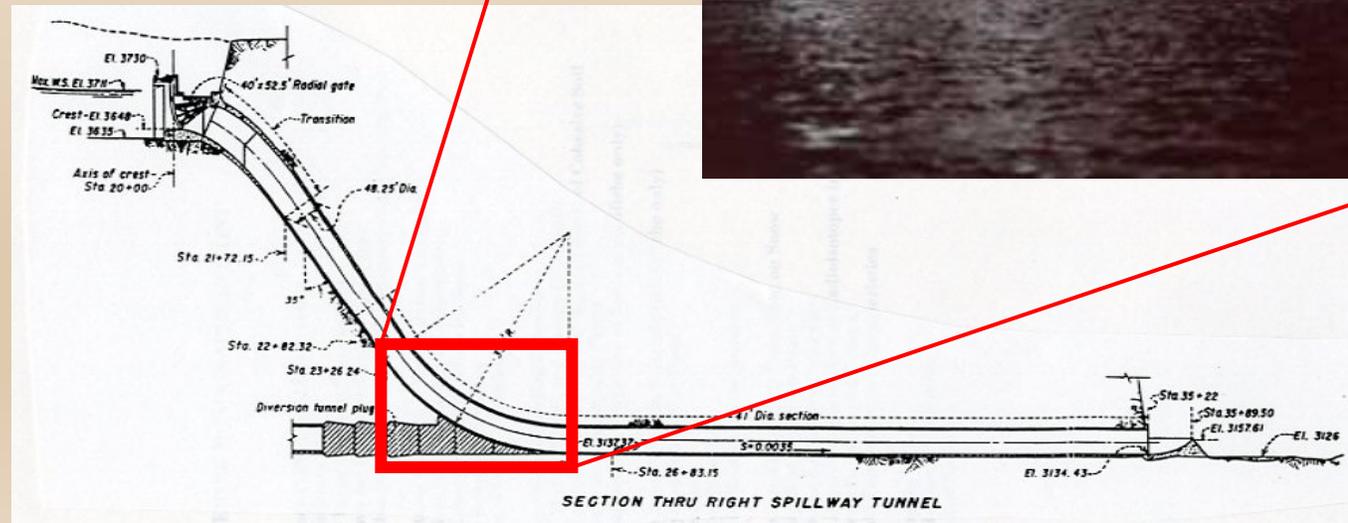
# Hoover Dam Spillway

- Arizona spillway tunnel operated for 116 days in Winter of 1941
- Tunnel lining failed and eroded an exposed fault
- Damage was attributed to a misalignment of the tunnel invert



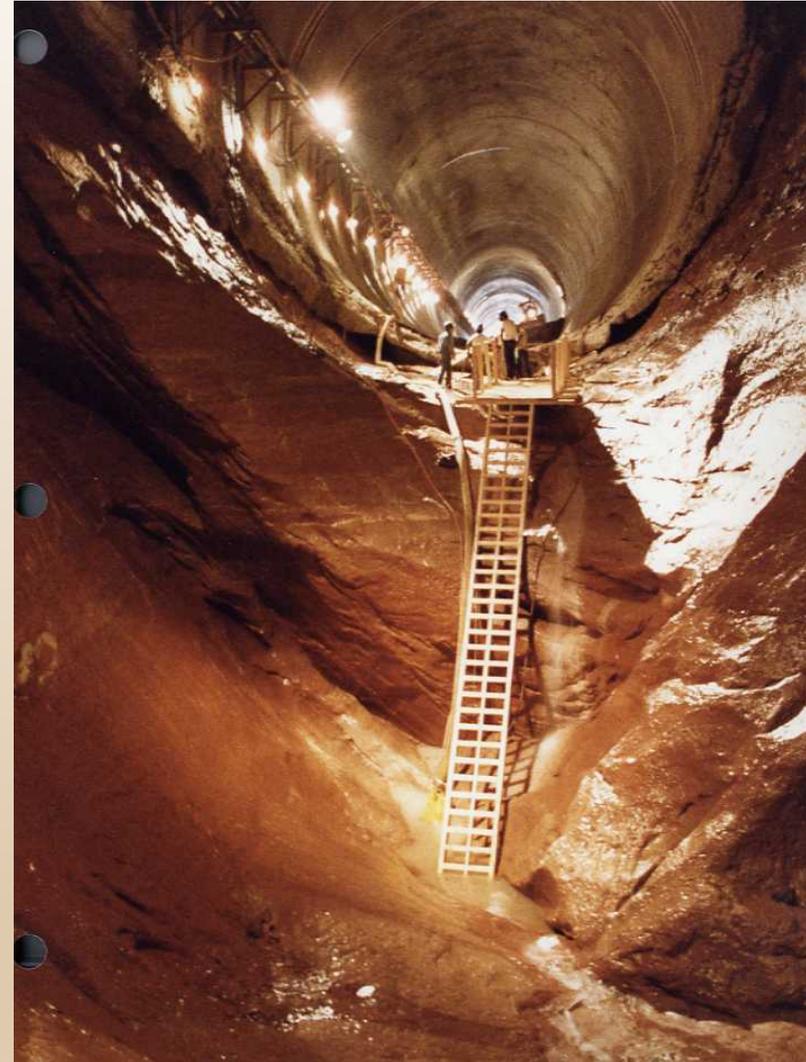
# Glen Canyon Dam Spillway

- 41-Foot-Dia. Tunnel with radial gates in each abutment.
- Combined discharge of spillways is 276,000 ft<sup>3</sup>/s at reservoir water surface El. 3711
- Initial attempts to minimize releases (<6000 ft<sup>3</sup>/s)
  - Right spillway ≈27,000 ft<sup>3</sup>/s
  - Left spillway ≈ 32,000 ft<sup>3</sup>/s
  - Outlets and power plant ≈ 44,000 ft<sup>3</sup>/s
  - Duration exceeded 45 days



# Glen Canyon Dam Spillway

- The cavitation damage was initiated by offsets formed by calcite deposits on the tunnel invert at the upstream end of the elbow
- Incipient cavitation indices of deposits along tunnel lining ranged from 0.64 to 0.73
- Cavitation indices of flow in areas where cavitation initiated in left tunnel spillway ranges from about 0.13 to 0.14 (1/4 to 1/6 range)
- Concrete lining repairs included the incorporation of air slots in both spillways



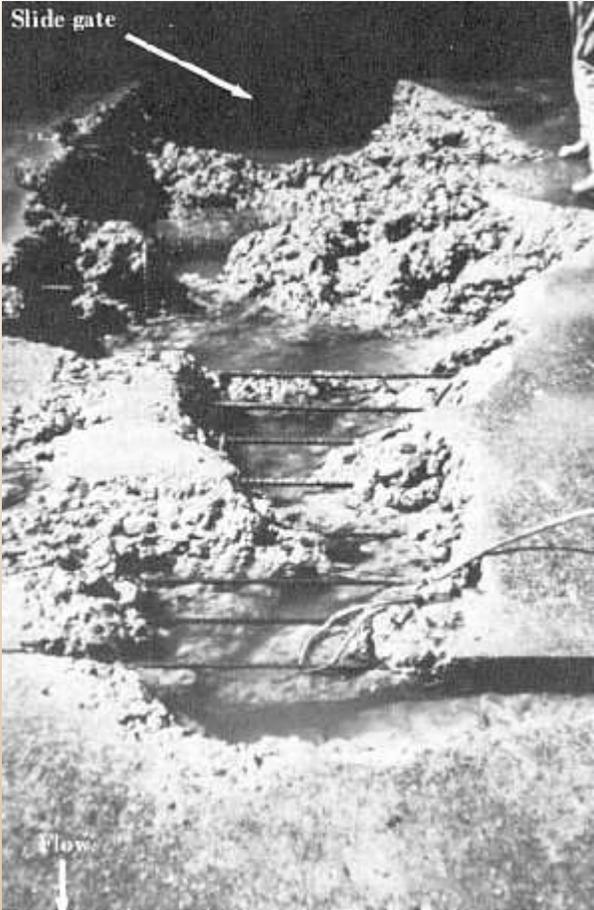
Left Spillway D/S of Elbow

# Libby Dam



- Sluice Outlets design head is 265-feet
- Severe Damage after 18 months of operation
- Majority of the damage was downstream of regulating gates
- Multiple other projects have experienced damage in this location

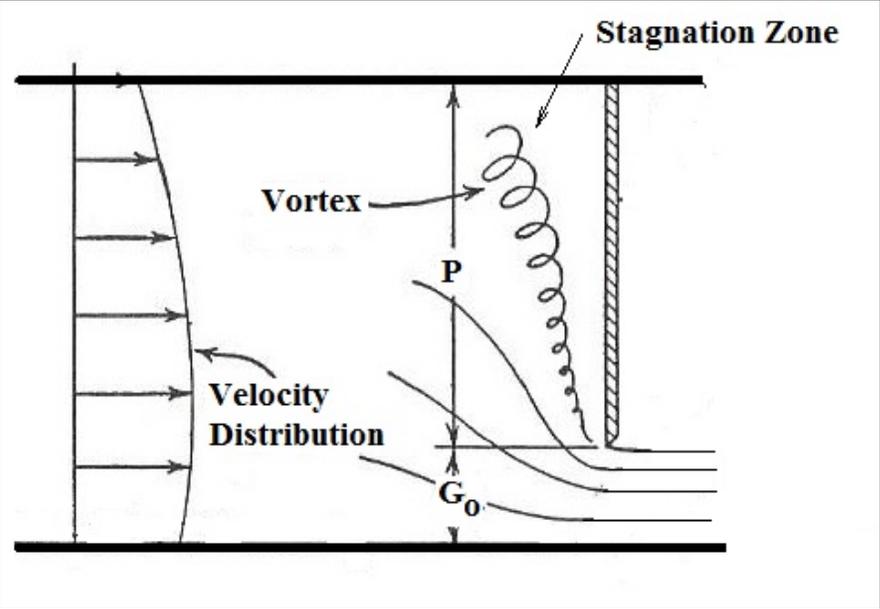
# Libby Dam and Palisades Dam



USBR – Palisades Dam



USACE – Libby Dam



# Typical Event Tree



# Typical Event Tree for Cavitation Damage

↳ Flows Conditions Exist to Create Cavitation

↳ Cavitation Damage Initiates

↳ Lining or Slab Fails

↳ Head Cut Initiates

↳ Unsuccessful Intervention

↳ Head Cut Progresses to Breach

# Key Considerations



# Key Considerations

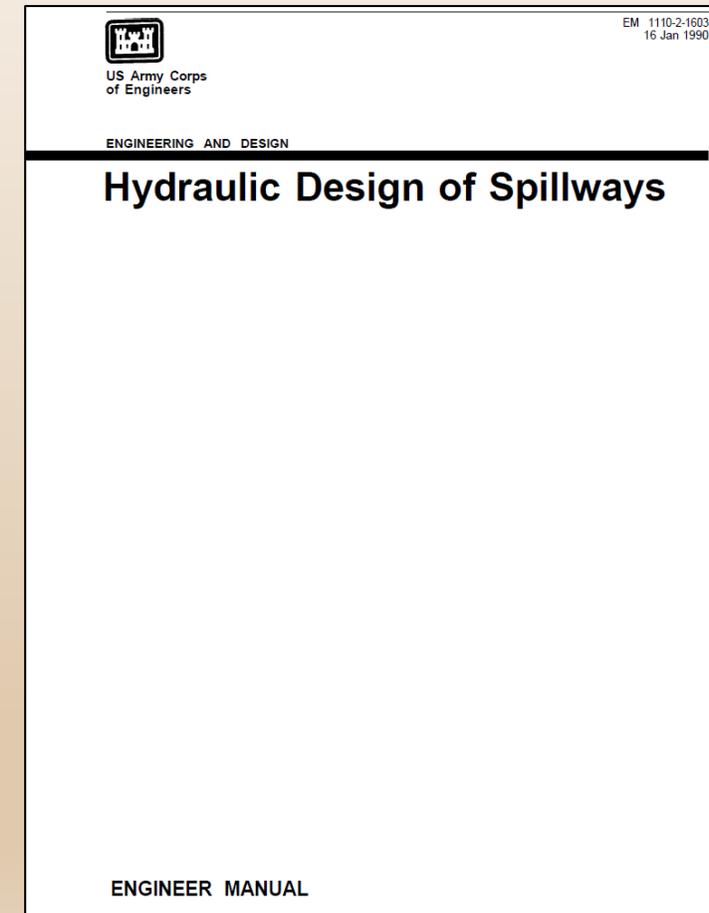
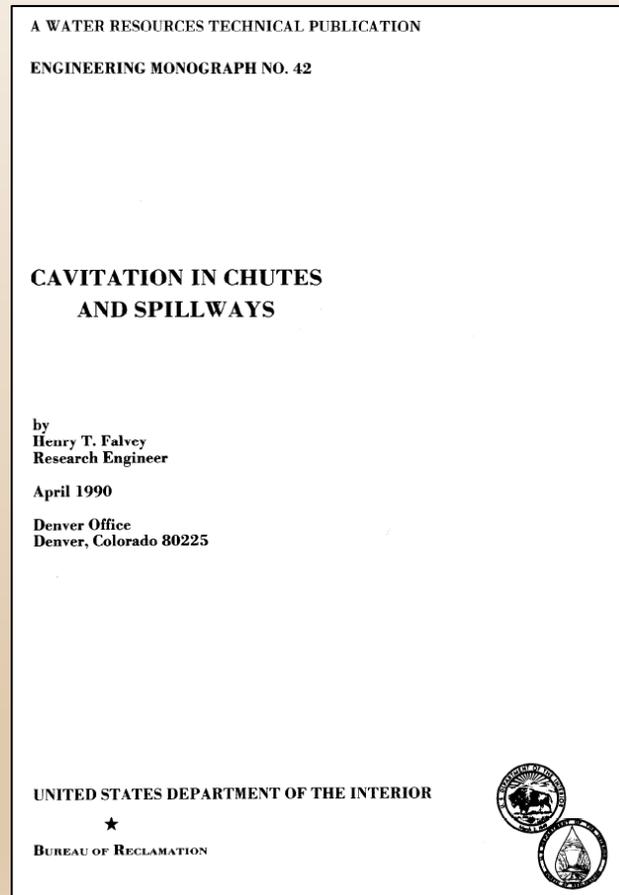
- Cavitation Indices (cavitation)
- Aeration of Flow (cavitation)
- Inspection Ability/Frequency
- Condition of Liner (usually concrete)
- Erodibility of Foundation Materials
- Duration and Frequency of Damaging Flows
- Ability to shut-off/decrease flow



# Analytical Methods



# Cavitation Damage



# Analytical Methods

$$\sigma = \frac{P_o - P_v}{\rho \frac{V^2}{2}} = \frac{H_o - H_v}{\frac{V^2}{2g}}$$

Where:

$P_o$  = Reference Pressure

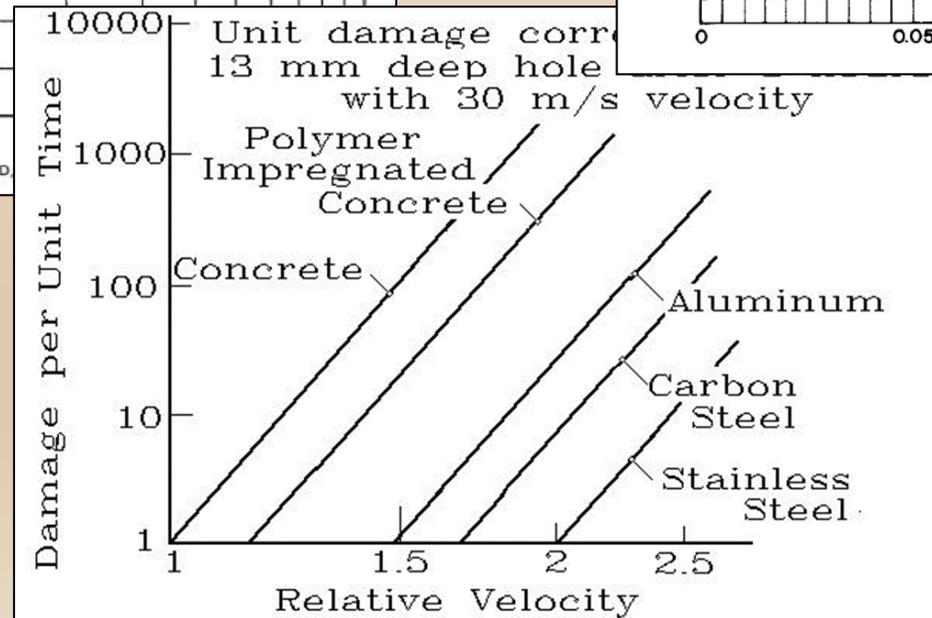
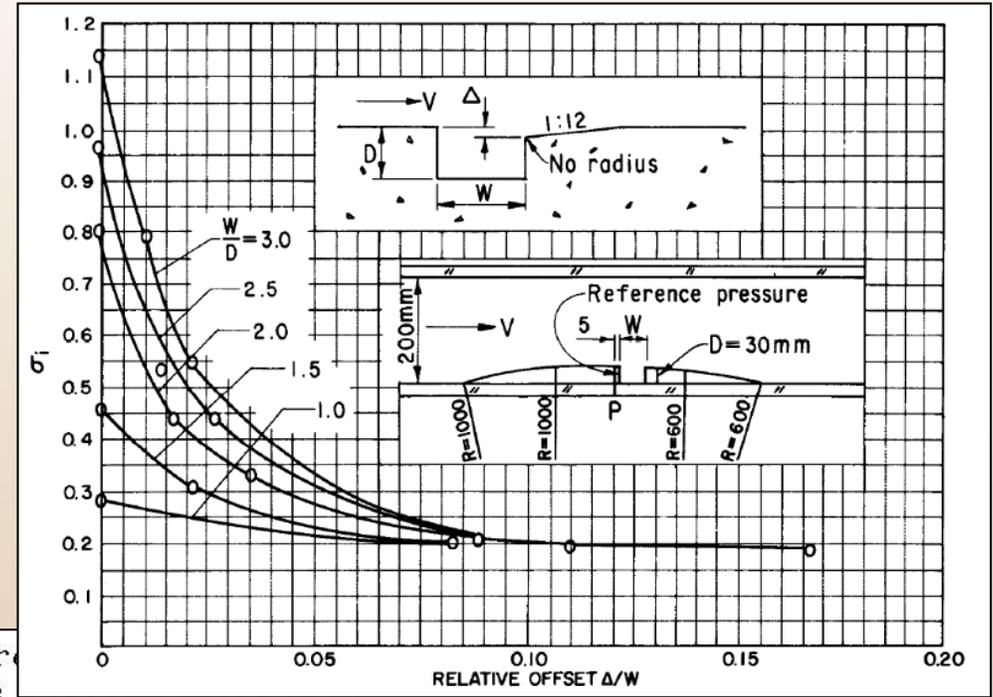
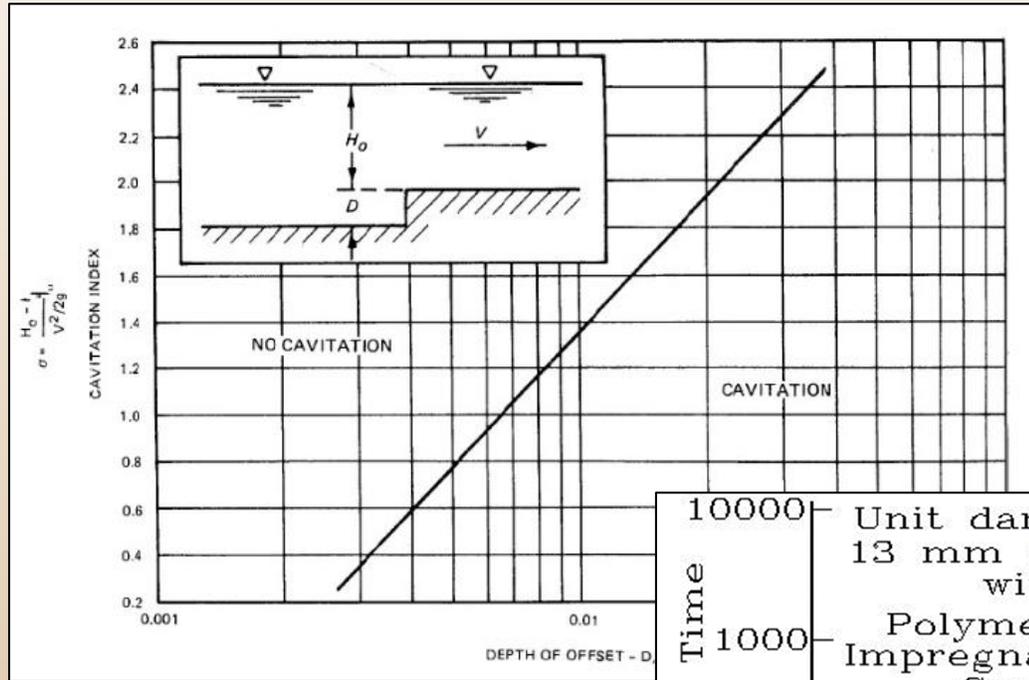
$P_v$  = Vapor Pressure

$V$  = Flow Velocity

$\rho$  = Density

- Cavitation Indices can be used to evaluate the potential for cavitation damage in a spillway chute or tunnel
- There is the potential for cavitation damage when the cavitation index is between 0.2 and 0.5, for typical concrete
- For large features introduced into the flow abruptly (stilling basin baffle blocks or splitter walls) cavitation damage can occur for indices as high as 1.0 or greater

# Analytical Methods



# Cavitation Damage

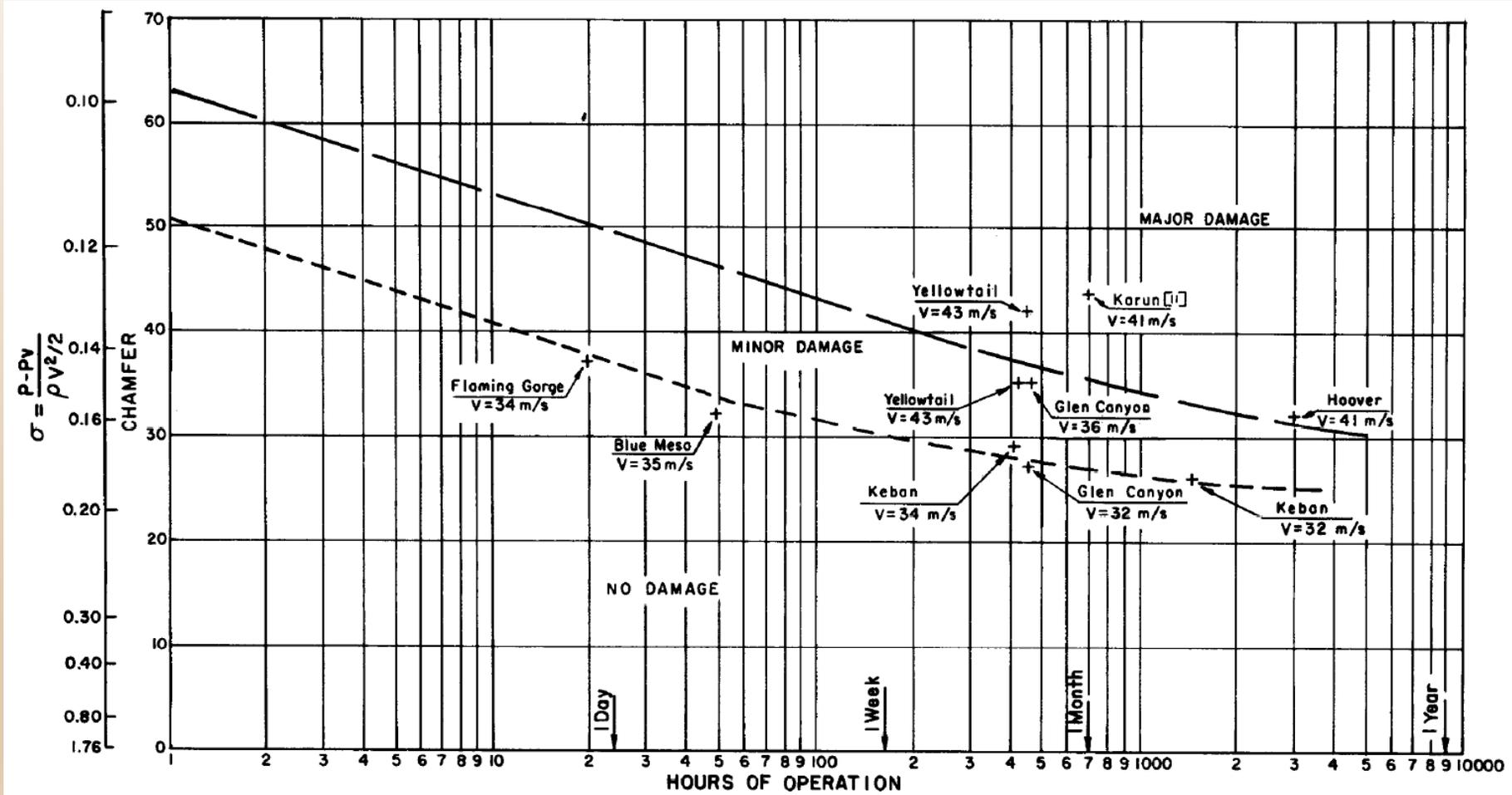


FIGURE 3-8.—Damage experience in spillways (Falvey [9]).

# Cavitation Damage

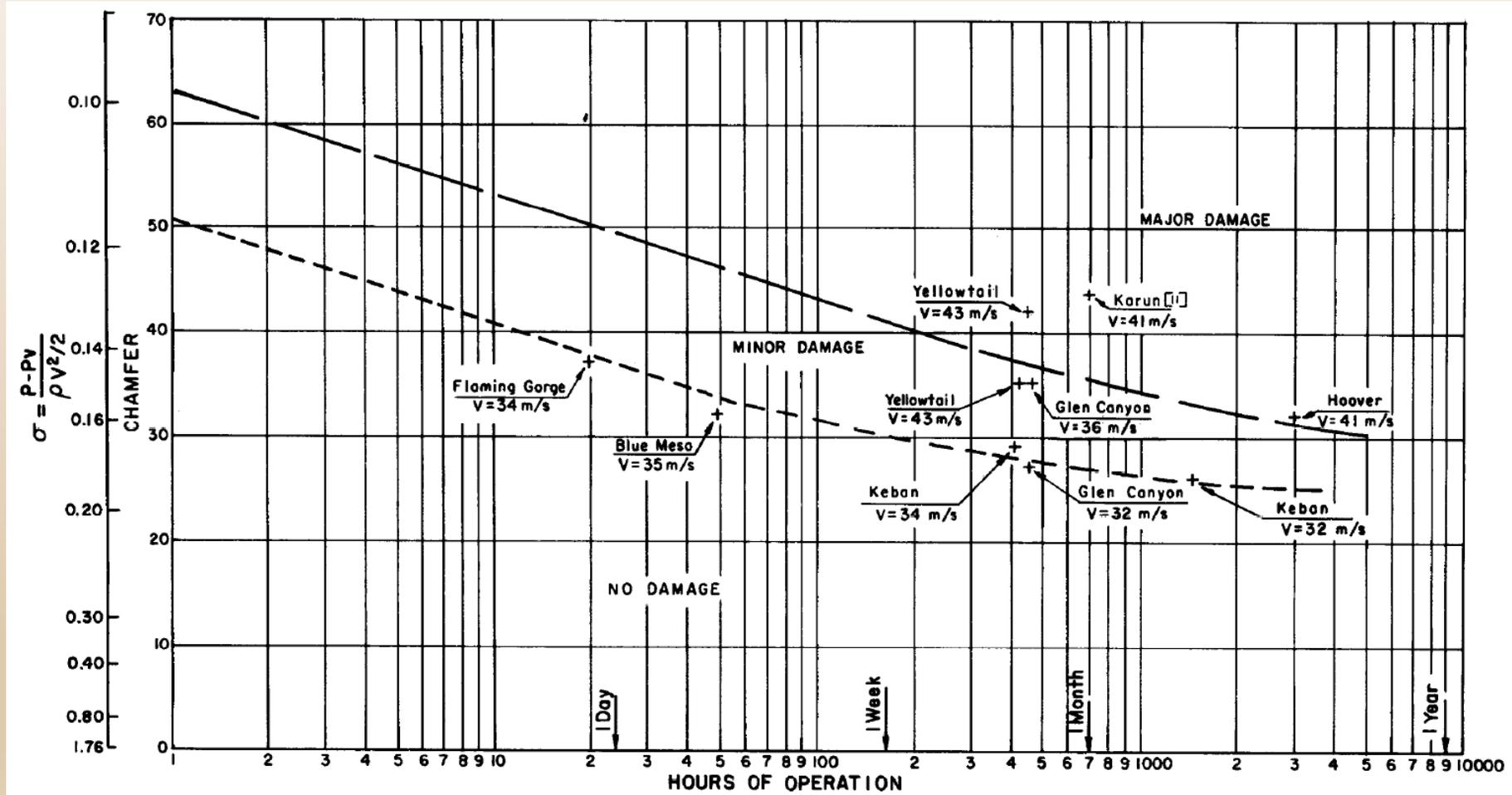
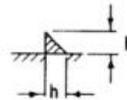
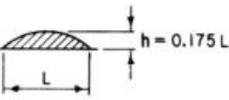
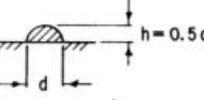
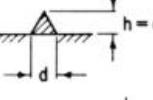
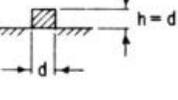
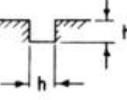
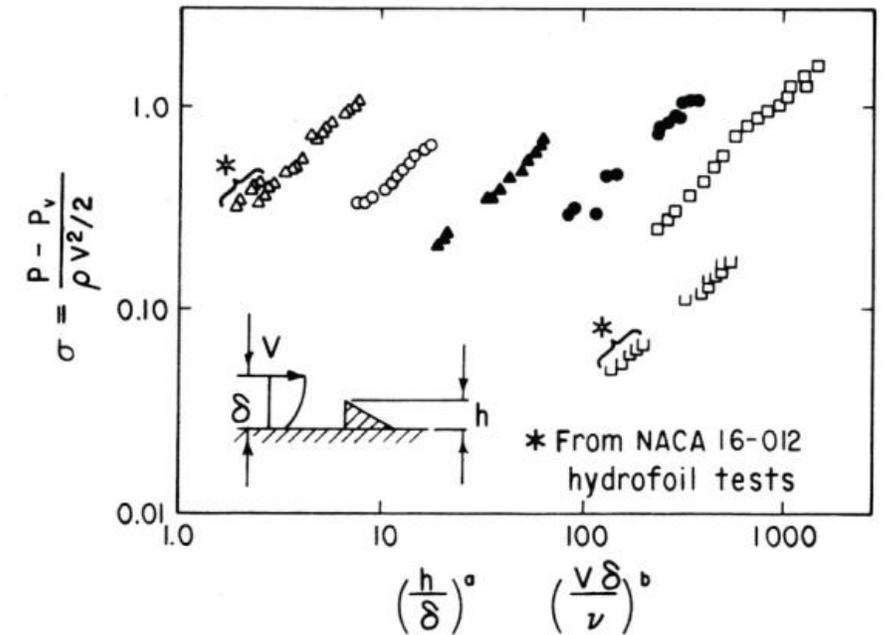


FIGURE 3-8.—Damage experience in spillways (Falvey [9]).

# Incipient Cavitation from Singular Offsets

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	



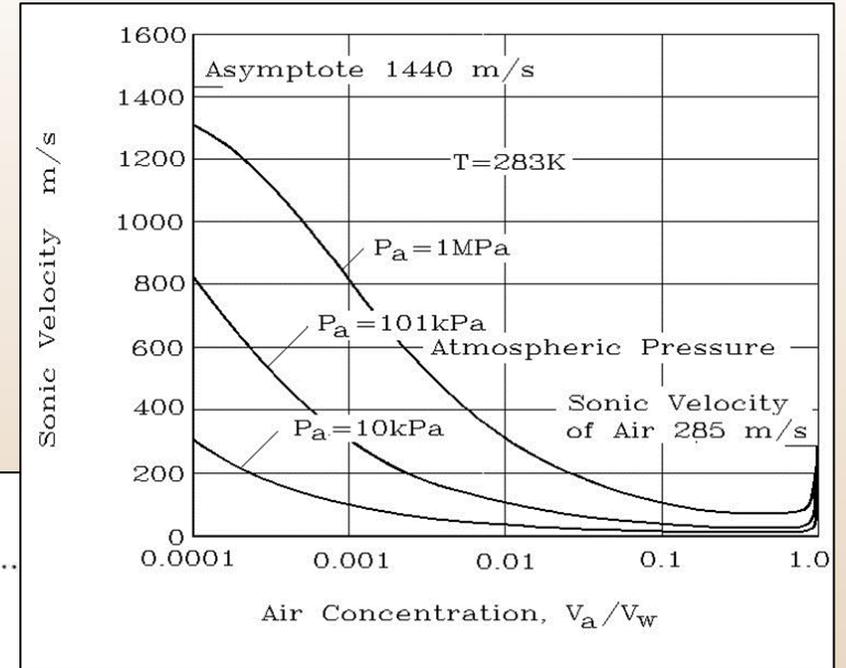
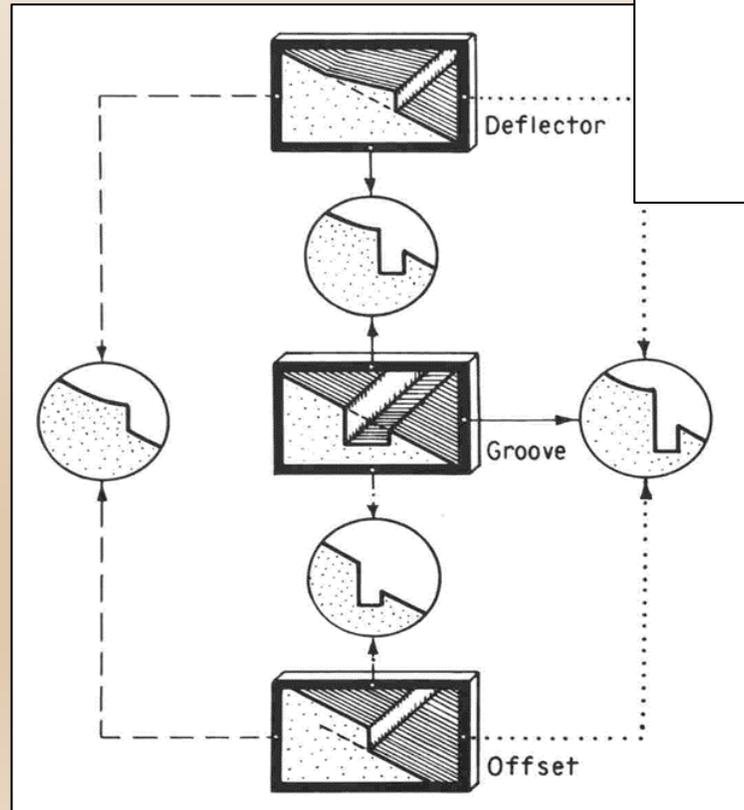
# Defensive Measures



# Defensive Methods

These items reduce the damage potential given a high cavitation potential is predicted

- Air Entrainment
- Polymerized Concrete
- Steel Liners
- Frequent Inspections and conduct repairs as necessary



# Takeaway Points

- Cavitation is a time dependent process
- Cavitation damage has resulted in significant damage to spillways at large dams
- There are simple ways of estimating the relatively likelihood of developing major damage due to cavitation
- Cavitation damage is often part of the initiation of an event tree and often transitions into erosion of soil or rock



# Questions



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