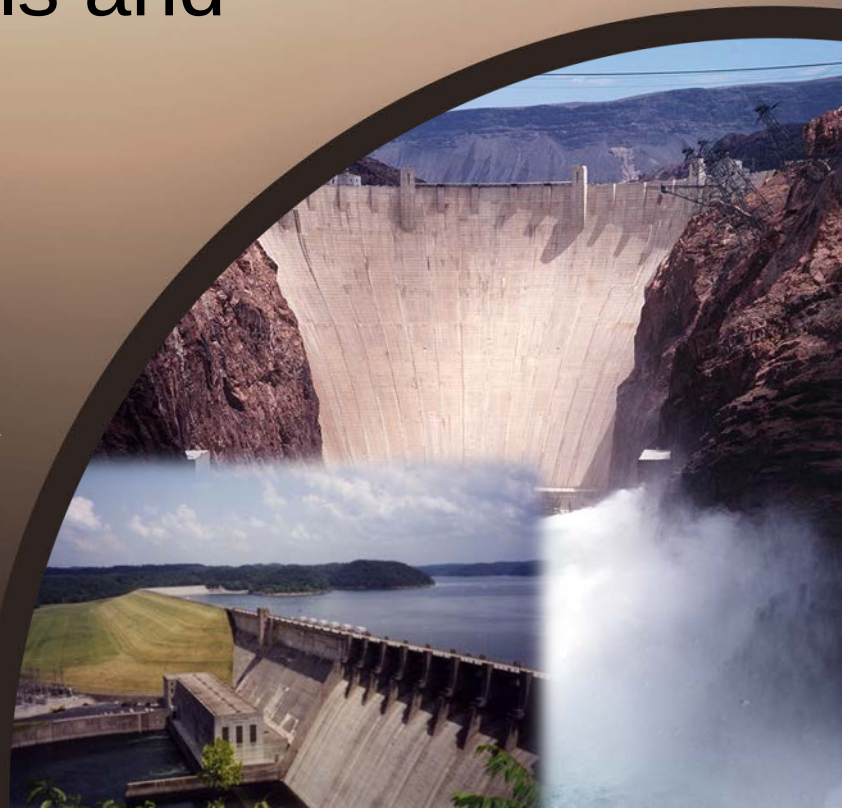
Best Practices in Dam and Levee Safety Risk Analysis

VI-1. Stagnation Pressure

VI-2. Overtopping of Walls and Stilling Basin Failure

VI-3. Cavitation

11 December 2014



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Managing Water in the West

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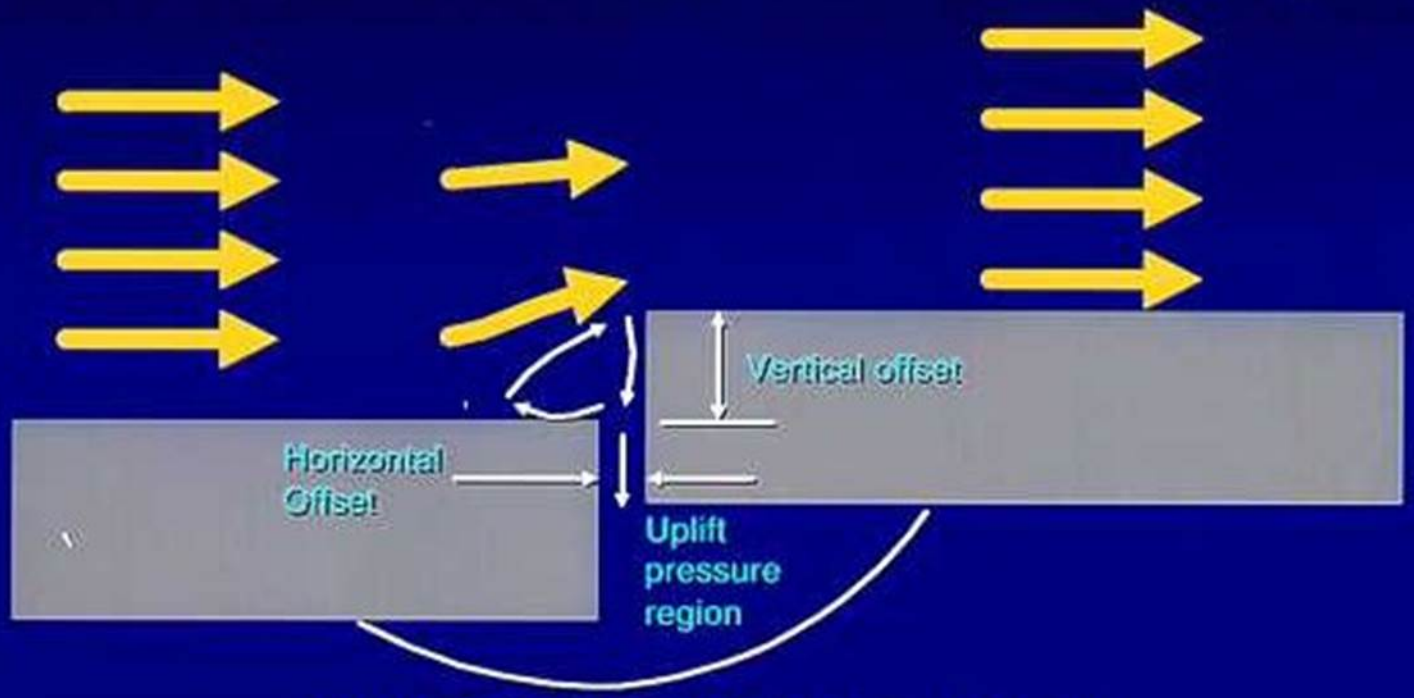
Stagnation Pressure and Cavitation Failure of Spillways

- Both potential failure modes are triggered by defects in the concrete flow surface
- Both require higher velocity flow
- Both can result in localized failure of the concrete lining of a spillway chute or tunnel and this can lead to erosion of the foundation

Stagnation Pressure

- Significant damage has occurred on several Reclamation spillways



Flow Pattern Over Displacement

Stagnation Pressure Failure

- Stagnation pressure enters joint and reaches foundation – High pressures/Significant flows
- Limited/Blocked Drainage Capacity
  - Pressures develop that exceed weight/anchorage
  - Hydraulic jacking removed slab
- Drainage
  - Erosion of foundation materials
  - Collapse of structure
- High velocity flow impact foundation leading to progressive erosion and headcutting

Key Factors – Stagnation Pressure

- Condition of Concrete in Spillway Chute
- Defensive Design Measures against Stagnation Pressures
- Flood Routing Results/Flood Frequency
- Spillway Discharges (Depths, Velocities and Durations)
- Erodibility of Foundation Materials
- Spillway Configuration

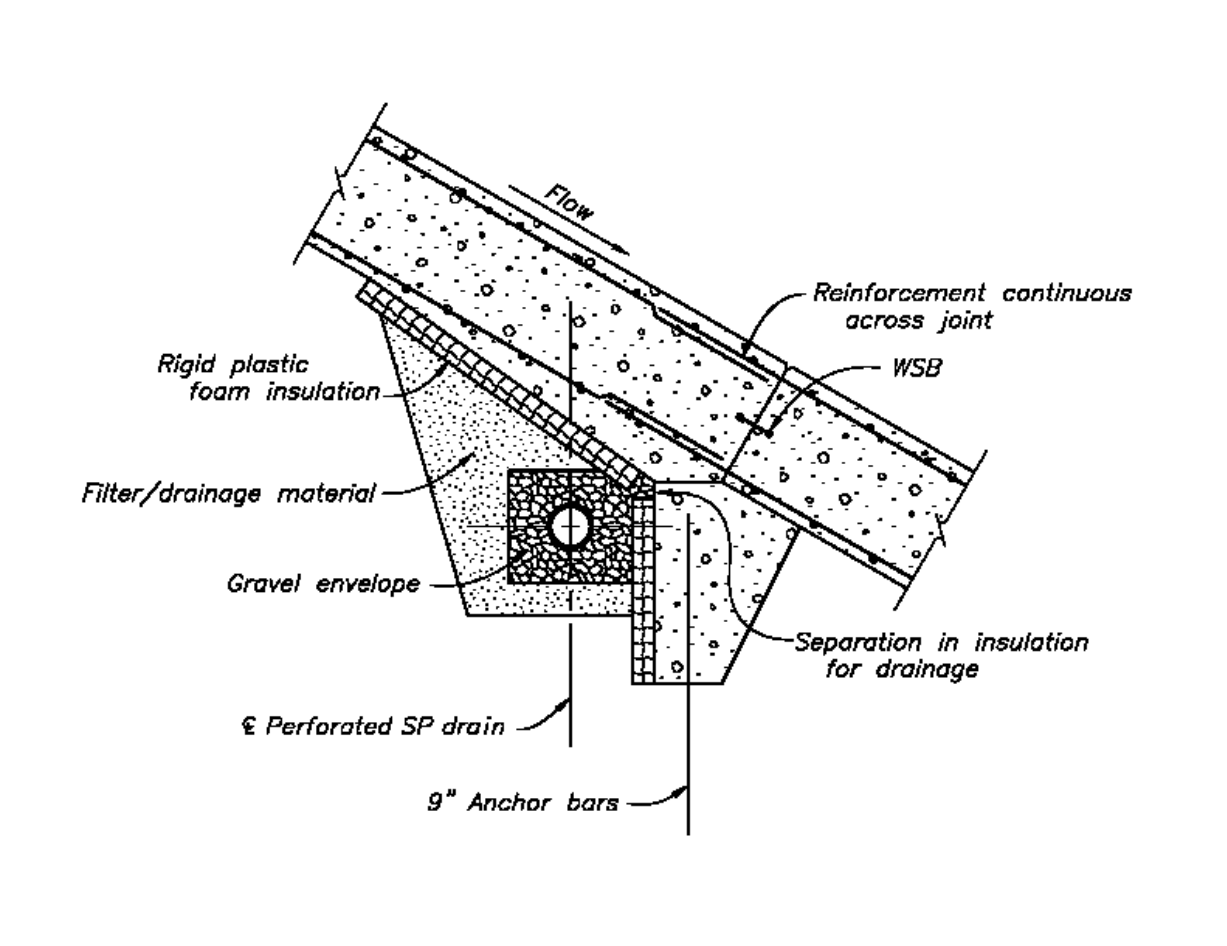
Condition of Concrete in Spillway Chute

- Vertical offsets into the flow are the primary concern for stagnation pressures
- Concrete deterioration in form of concrete delamination, alkali-silica reaction, freeze-thaw damage and sulfate attack can exacerbate this failure mode by initiating cracks, causing localized damage, opening cracks and joints in chute concrete, creating offsets into the flow and creating separation of chute from foundation
- Recent exam is needed to assess condition

Defensive Design Measures – Stagnation Pressures

- Defensive design measures can prevent the failure mode from initiating or progressing
  - Waterstops – prevent flow through joints
  - Transverse cutoffs – prevent vertical offsets and restricts seepage path through slabs
  - Longitudinal reinforcement – minimize width of cracks/joint openings and may prevent offsets
  - Anchor bars – provides resistance to jacking pressures
  - Filtered underdrains – relieves uplift pressures
  - Insulation – prevents drainage system from freezing

Defensive Design Measures



Flood Routing Results/Flood Frequency

- Routings of specific frequency floods provides discharges and discharge durations for a flood of a given return period
- Flood return periods used to generate flood load ranges and load range probabilities

Spillway Discharges (Depths, Velocities and Durations)

- Water surface profiles are typically calculated for discharges obtained from frequency flood routings
- Water surface profiles provide flow depths and velocities at selected stations along chute
- Flow velocities at joints and cracks are used to estimate uplift pressures and flow volumes at these locations
- Lateral and upstream extent of uplift pressures and foundation seepage flows will be a function of drainage, permeability of foundation, bonding (or separation) of slab to foundation and will require judgment and includes uncertainty

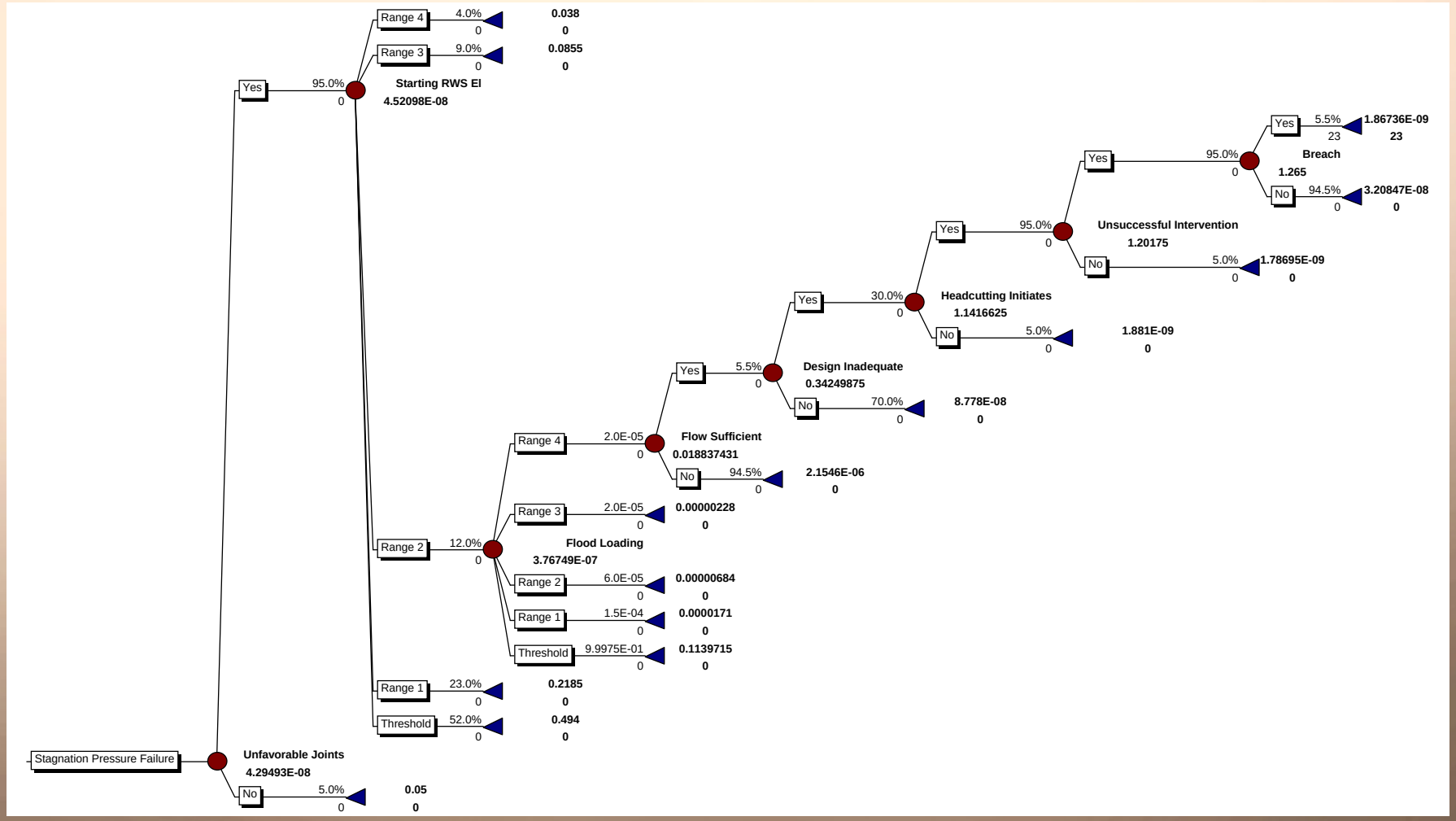
Erodibility of Foundation Materials

- Soil foundations are generally more erodible than rock foundations
- If erosion of foundation materials initiates and progresses, chute slab can be undermined and may collapse
- If slab fails due to jacking, foundation will be exposed to spillway flows directly
- Foundation can scour and headcutting can initiate

Spillway Configuration

- Uncontrolled spillways are not regulated and provide little or no opportunity to reduce discharges or redirect flows should problems develop during a flood
- Gated spillways may allow for reduction in spillway flows and reliance on reservoir surcharge space, especially for smaller floods
- For spillways with multiple gates it may be possible to operate gates to direct flow away from damaged area, at least in upper chute
- Spillways with monolithic walls/slabs or with reinforcement across longitudinal joints will mobilize walls and backfill over heels to resist uplift

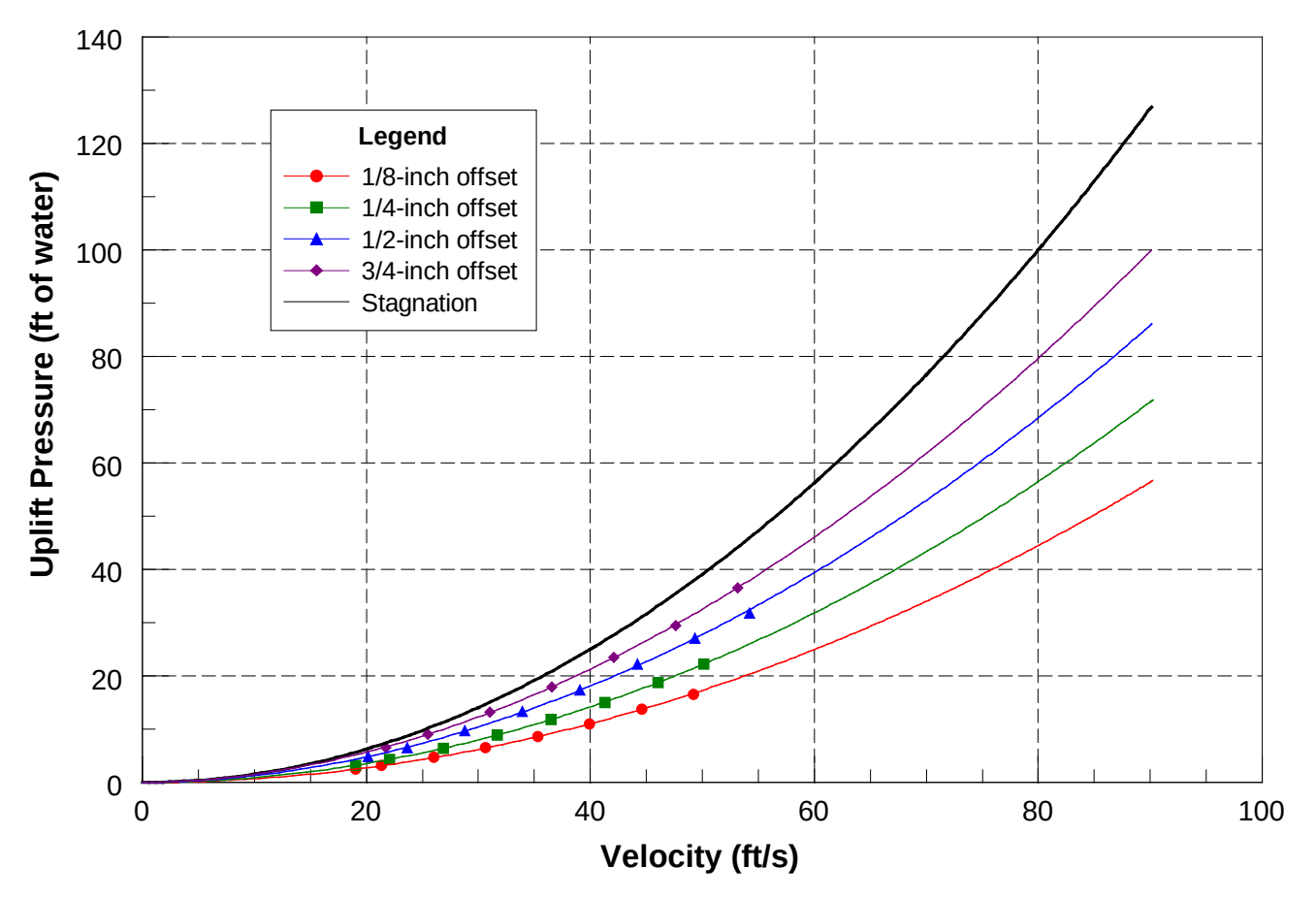
Example Event Tree – Stagnation Pressure



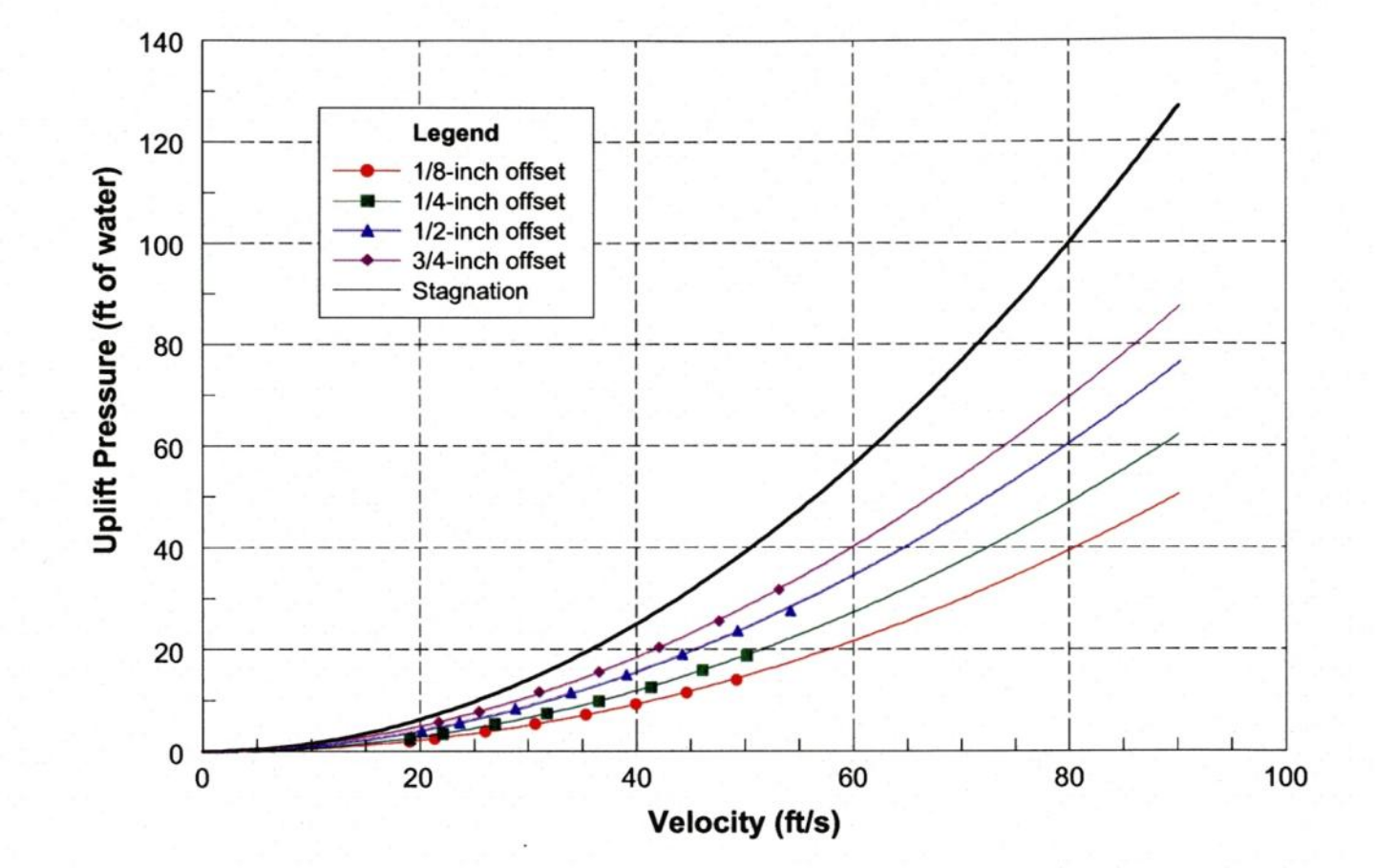
Stagnation Pressure and Flow - Laboratory Tests

- Tests were conducted in 2007 to expand the conditions over which stagnation pressures had been evaluated
- Transverse joints with variable offsets and gaps were evaluated for different flow velocities
- Tests were conducted with a water filled cavity under the slab that was sealed for some tests and vented (representing drainage) for other cases
- Water filled cavity in test may allow for more rapid and complete response than would occur in actual foundation
- Sealed condition represents maximum uplift pressure that would be expected for joint geometry
- For drained conditions, uplift pressures and flows for vented cases need to be considered together
- Drain in test was arbitrarily sized

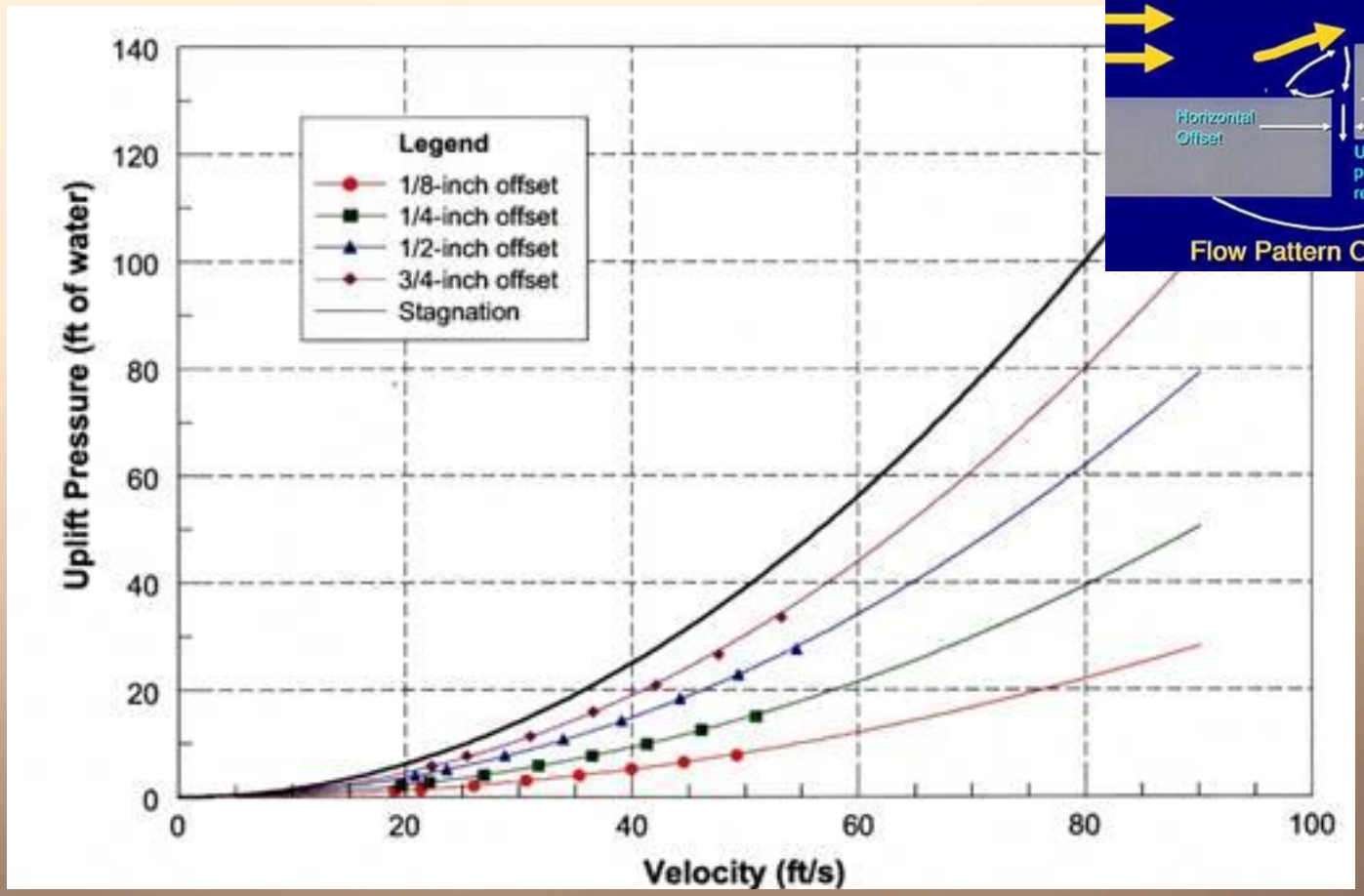
Mean Uplift Pressure, sharp edged geometry, sealed cavity, 1/8-inch gap

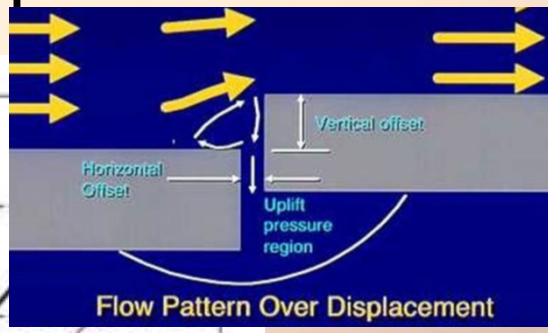


Mean Uplift Pressure, sharp edged geometry, vented cavity, 1/8-inch gap

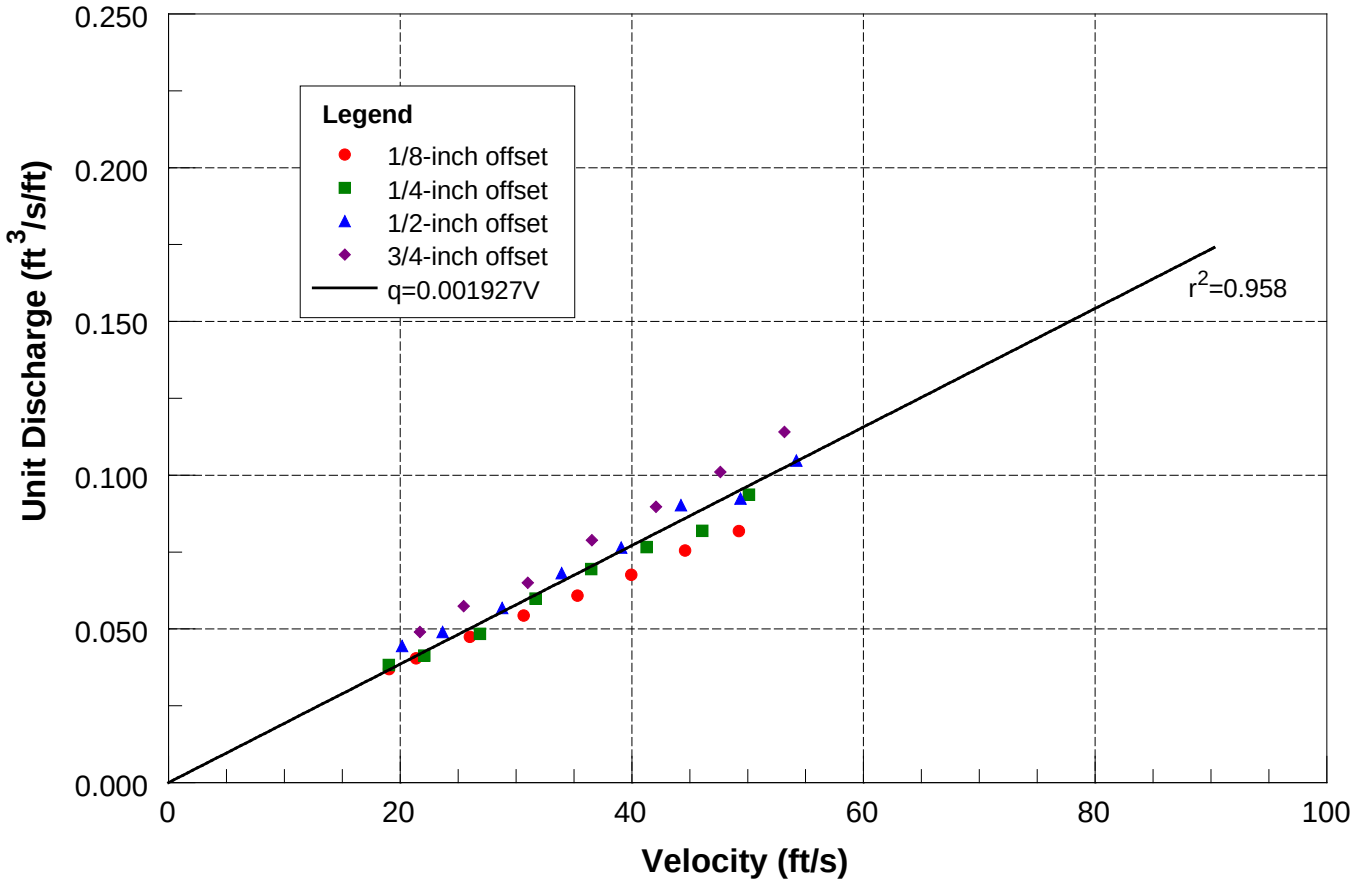


Mean Uplift Pressure, sharp edged geometry, vented cavity, 1/2-inch gap

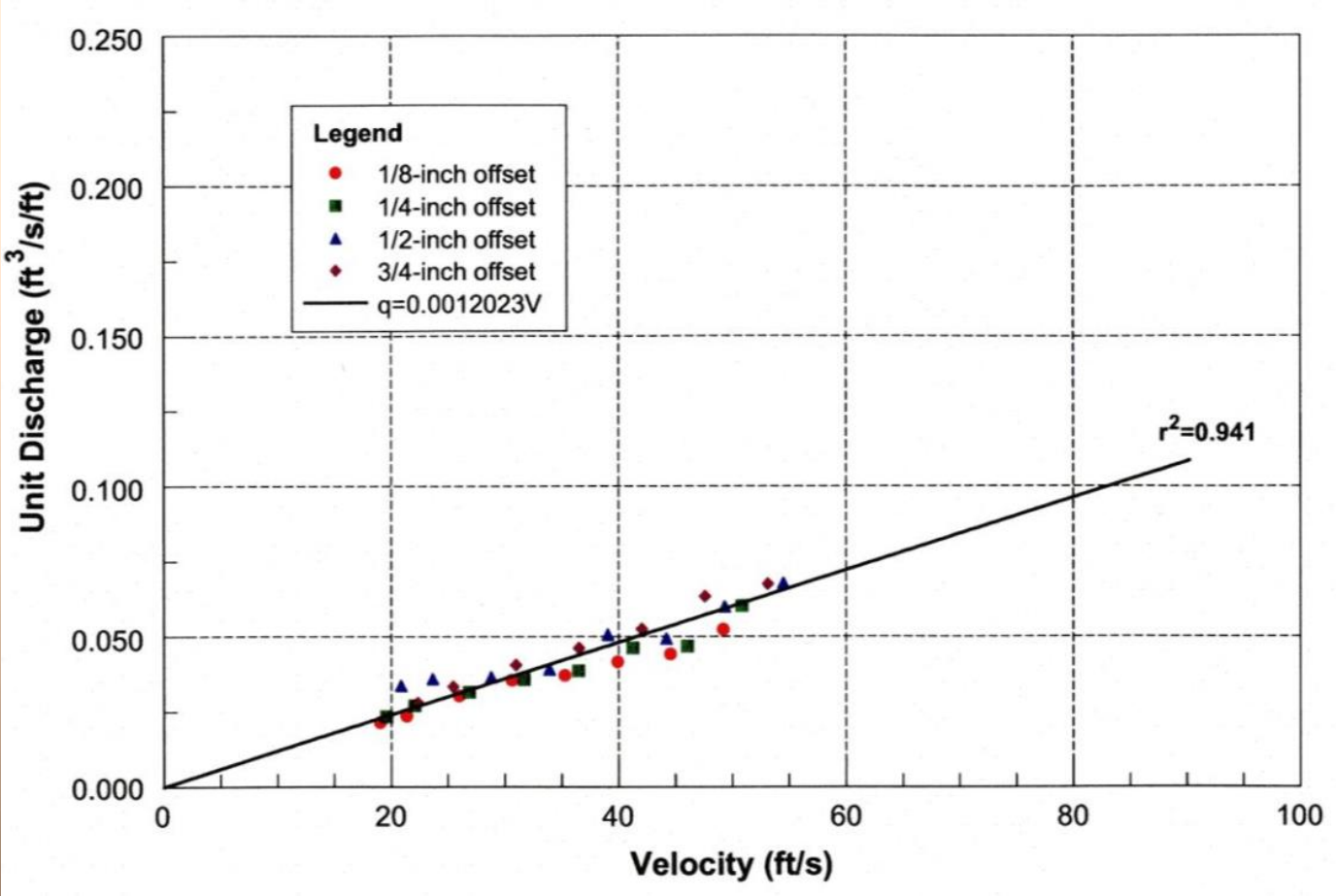




Unit Discharge for Joint/Crack sharp edged geometry, 1/8-inch crack



Unit Discharge for Joint/Crack sharp edged geometry, 1/2-inch crack



Slab Jacking

- Lateral extent of offset into flow is important – limited offset will limit extent
- Area of slab subjected to uplift pressure is factor in jacking potential
- Stagnation pressure flows may overwhelm drain capacity
- Judgment required in slab jacking calculations

Foundation Erosion

- Lateral extent of offset into flow is important – limited offset will limit total flow
- Stagnation pressure flows may overwhelm drain capacity
- Longitudinal open cracks also create the potential for seepage to be introduced into the foundation
- Foundation erosion can be evaluated as an internal erosion failure mode

Big Sandy Dam Spillway

- Portions of spillway chute and stilling basin slabs began deteriorating shortly after the dam put into service in 1951
- Cracking occurred in the chute and stilling basin slabs due to combination of excessive water and ice pressures along the rock-concrete interface
- Movement of some of the slabs away from the foundation was evident
- Drainage under slabs was inadequate and anchor bars not sufficient to prevent slab lift off

Big Sandy Modified Spillway

Erosion in Spillway Floor (1980)

Big Sandy Dam Spillway

- Spillway operated without incident from 1957 to 1983
- Chute floor slab failed in June 1983 due to uplift pressures from flows of 400 ft^3/s
- Chute inspected after releases ended
- 15-inch thick slab was lifted 2 feet off its foundation
- Later determined that slab failed due to static and dynamic water pressures under the slab
- Offsets (vertical and horizontal openings) existed at the upstream edge of the slab allowed water to introduce flow under the slab

Big Sandy Spillway
Stagnation Pressure Failure

Big Sandy Spillway
Stagnation Pressure Failure

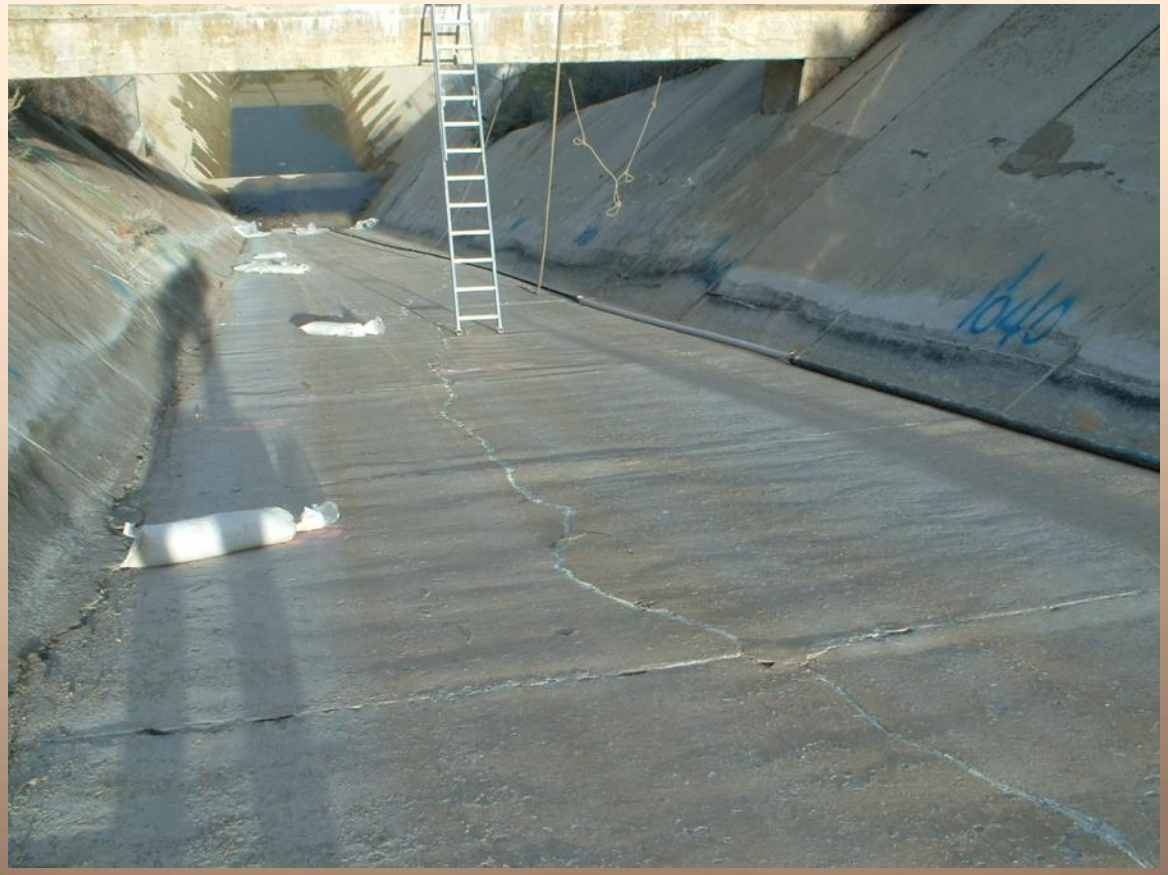
Uplift Calculations

- Big Sandy Spillway Slab failed between stations 4 + 66.87 and 4 + 85.85, during spillway discharge of 400 ft^3/s
- Failure was initiated by offset into flow at station 4 + 66.87 (depth of flow – 0.3 ft; velocity – 31 ft/s)
- Assuming 1/8 inch open joint, vertical offset of 0.50 inches and anchor bars only 50 percent effective, slab would fail
- With anchor bars fully effective, slab would not have failed
- Analysis of slab evaluated 1 foot wide slab section from station 4+66.87 to station 4+85.85
- Stagnation pressure assumed constant over entire slab
- From observations after failure, anchor bars exposed beneath slab were not coated with grout

Foundation Erosion Due to Stagnation Pressure

Foundation Erosion

Slab Settlement Due to Foundation Erosion



Cavitation

- Cavitation is the formation of vapor cavities in a liquid
- 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)
- The extent of cavitation damage will be a function of the cavitation indices at key locations in the spillway, the characteristics of the flow surface irregularity and the duration of spillway flows

Cavitation Damage Induced Failure

- High velocity flows cause cavitation leading to damage of the structure
- Damage progresses until the lining fails and flows have access to foundation materials
- Progressive erosion and headcutting work upstream
- This failure mode is unlikely to progress to the point of dam failure, in most cases, due to the long durations that would be required to cause significant damage to concrete lining

Event Tree Cavitation Damage

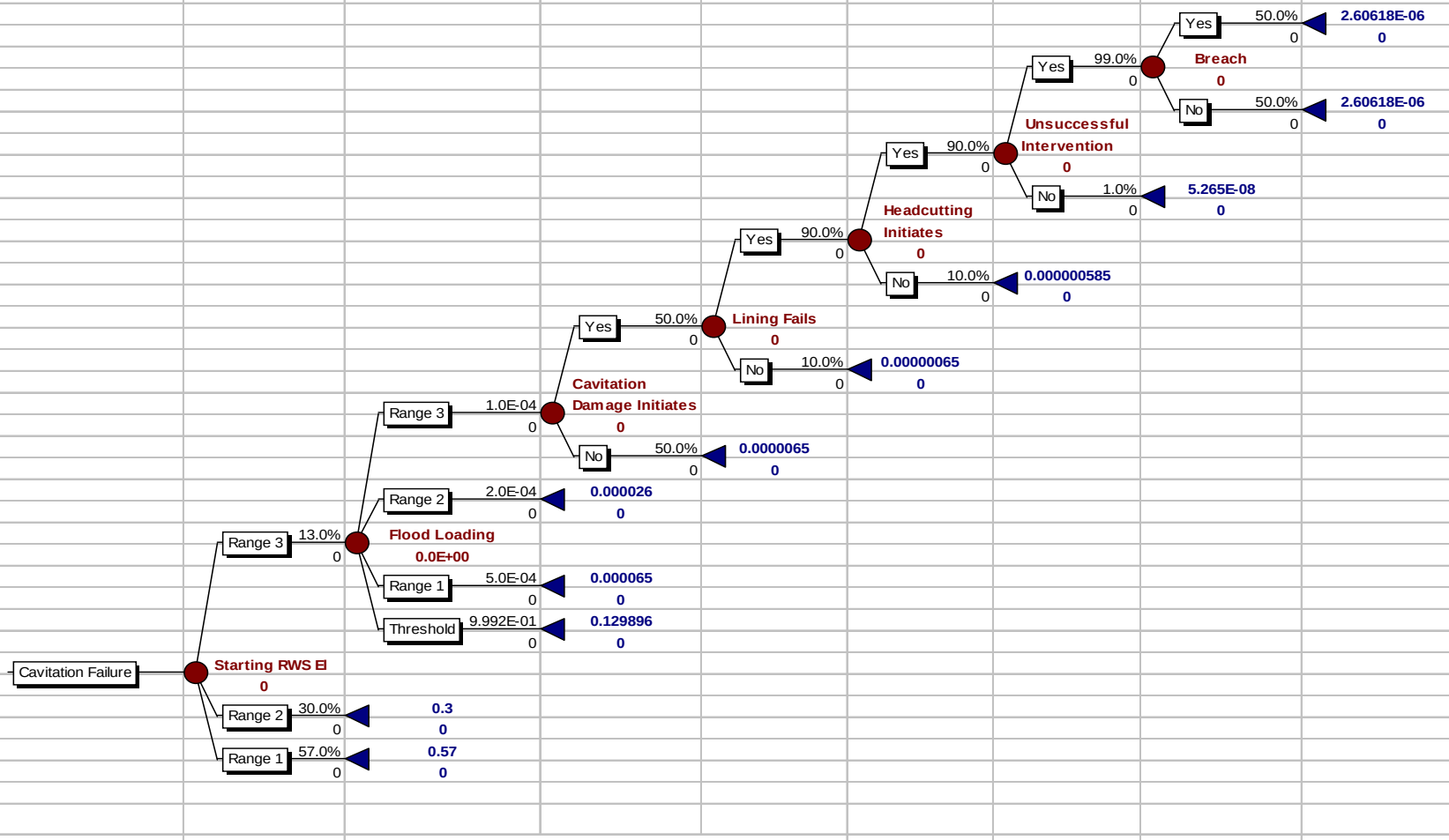


Figure 21-2 - Example Event Tree

Key Factors – Cavitation Damage

- Condition of Concrete in Spillway Chute
- **Cavitation Indices (cavitation)**
- **Aeration of Flow (cavitation)**
- Flood Routing Results/Flood Frequency
- Spillway Discharges (Depths, Velocities and Durations)
- Erodibility of Foundation Materials
- Spillway Configuration

Cavitation Indices

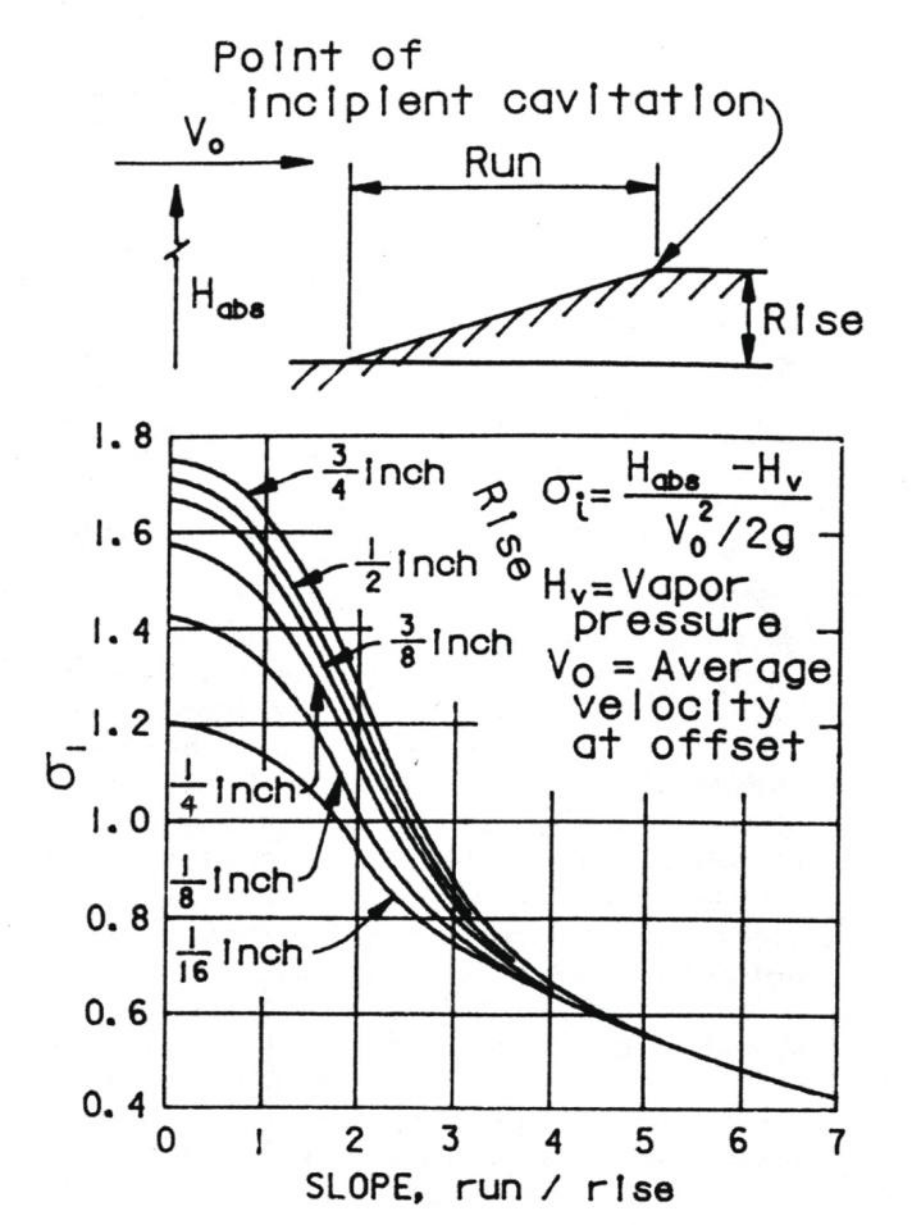
- Cavitation Indices can be used to evaluate the potential for cavitation damage in a spillway chute or tunnel
- There is the potential for cavitation damage when the cavitation index is between 0.2 and 0.5, for typical concrete
- For large features introduced into the flow abruptly (stilling basin baffle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

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

Phases of Cavitation

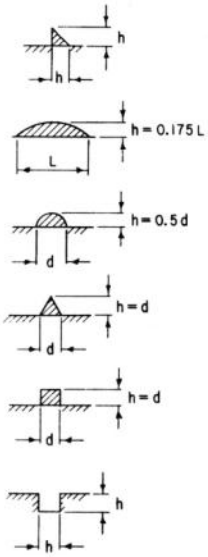
- Incipient Cavitation – occasional cavitation bubbles form in flow; **damage occurs at one-sixth to one fourth of this value**
- Developed Cavitation – many small cavitation bubbles are formed, appearing as a white fuzzy cloud
- Supercavitation – large vapor cavities are formed from individual cavitation bubbles

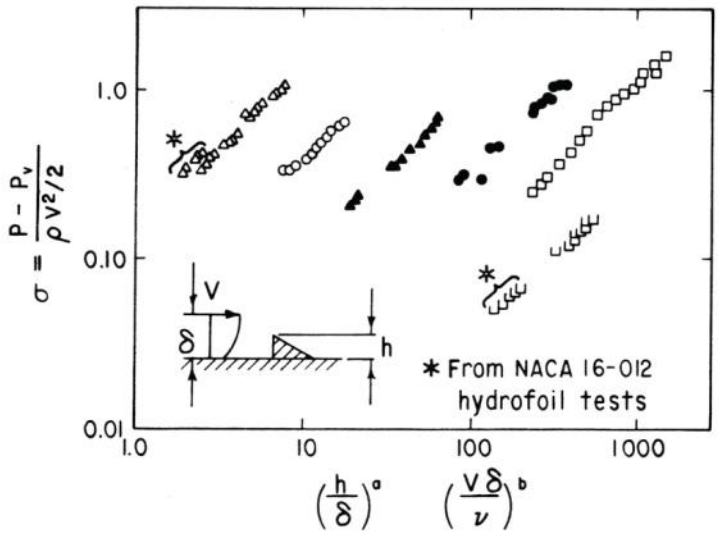
Incipient Cavitation



Incipient Cavitation

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





Cavitation Damage

- Cavitation damage is not constant with time
- Incubation period - at first, loss of material does not occur; surface becomes pitted
- Accumulation period – damage rate increases rapidly and peaks
- Attenuation phase – damage rate decreases
- Significant damage takes time to develop **<u>and the time is cumulative</u>**

Cavitation Damage

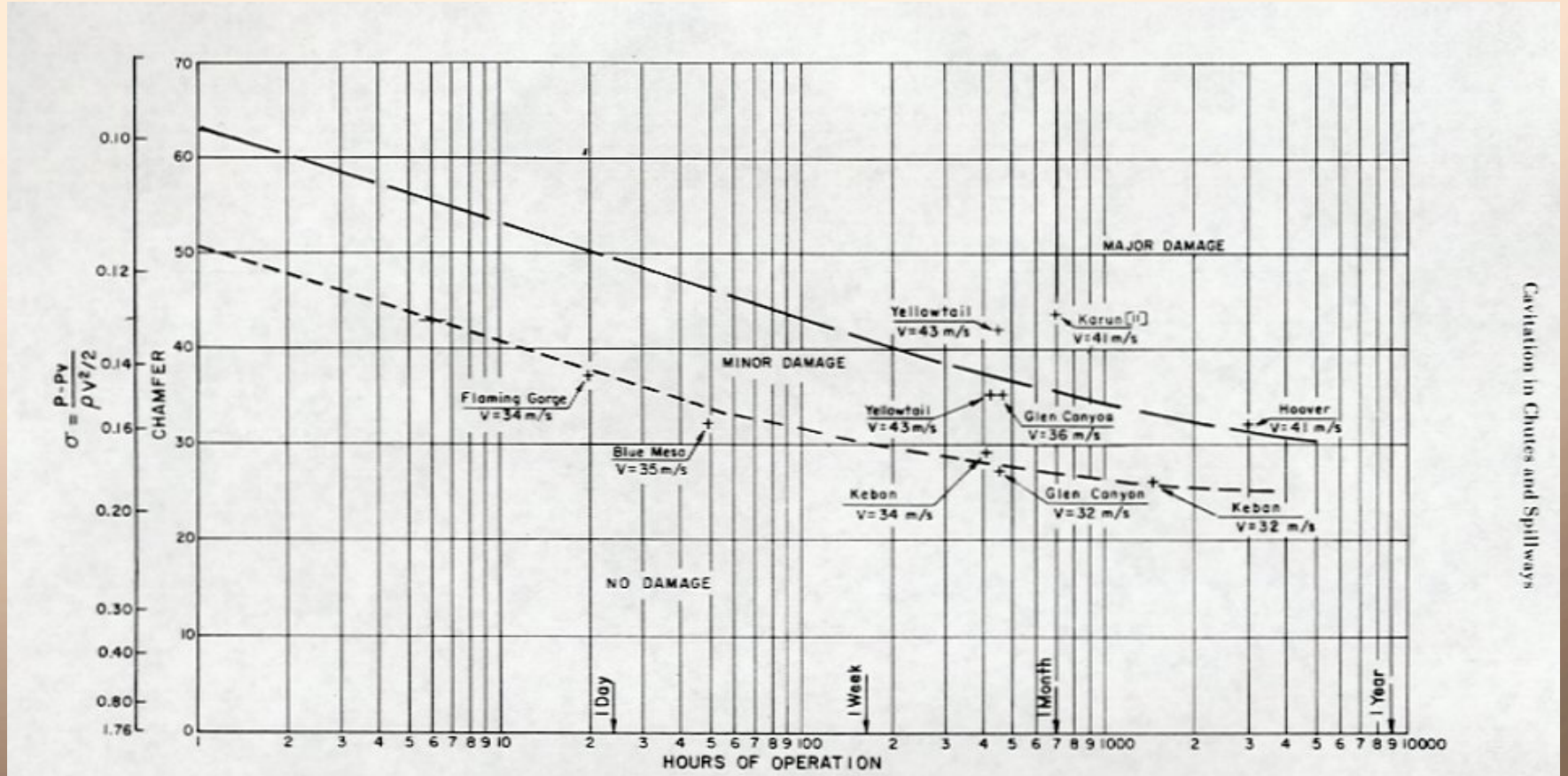


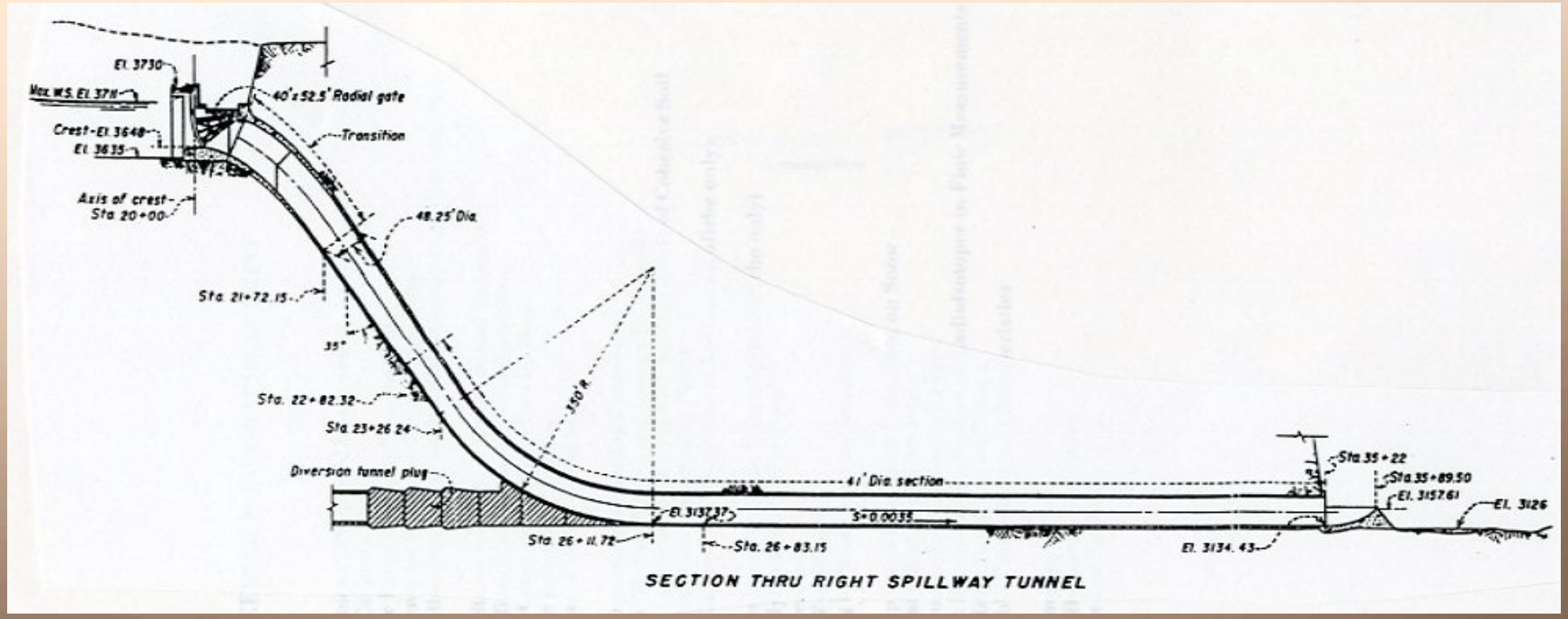
FIGURE 3-8.—*Damage experience in spillways (Falvey [9]).*

Aeration of Flow - Cavitation

- 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 flow is not naturally aerated, measures can be taken to introduce air into the flow at critical locations along the spillway
- Existing air ramps/air slots should be evaluated for effectiveness at flows beyond their design capacity

Glen Canyon Dam Spillway

- 41-Foot-Dia. Tunnel with radial gates in each abutment.
- Combined discharge of spillways is 276,000 ft^3/s at reservoir water surface El. 3711



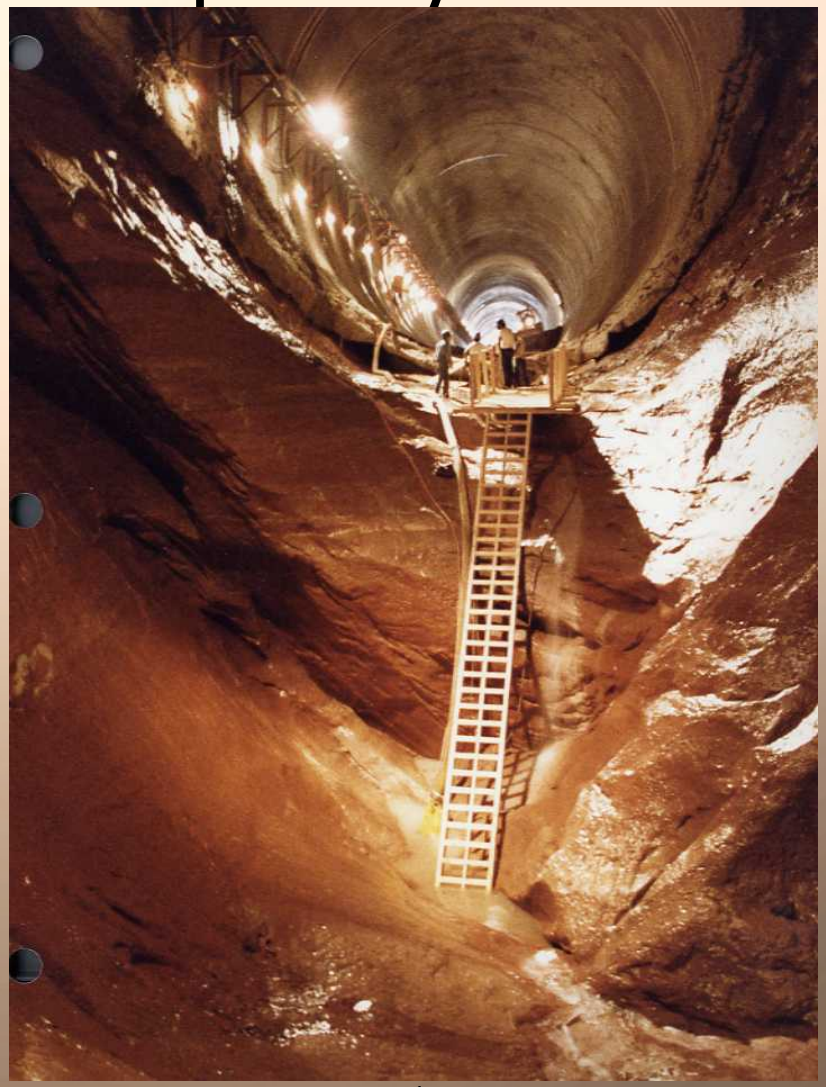
SECTION THRU RIGHT SPILLWAY TUNNEL

Glen Canyon Dam Spillway

- May 1983 Colorado River watershed extremely large snowpack
- Left spillway
  - June 2 – 10,000 ft^3/s
  - June 5 – Increase to 20,000 ft^3/s
  - June 6 – Tunnel was inspected due to loud rumbling and several large holes were found in the invert of the elbow

Glen Canyon Dam Spillway

- Initial attempts to minimize releases (<6000 ft^3/s)
  - Right spillway ≈27,000 ft^3/s
  - Left spillway ≈ 32,000 ft^3/s
- 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

Spillway Wall Overtopping and Stilling Basin Failure Key Concepts and Factors

- Spillway Design Discharge
- Spillway Discharges (Depth and Duration)
- Convergence and Divergence of Chute Walls
- Superelevation of Chute
- Air Bulking in Flow
- Cross Waves in Spillway Chutes
- Spillway Configuration
- Ball Milling
- Stilling Basin Sweepout

Spillway Design Discharge

- The discharge that the spillway was designed for will determine the flow capacity of the chute and stilling basin
- If flood routings indicate spillway design discharge will be exceeded for some flood events, chute overtopping becomes more likely
- Whether overtopping occurs will be influenced by freeboard provided in the original design and other factors (cross waves and air bulking)
- Stilling basin walls not typically a concern regarding overtopping (distance from crest and tailwater)

Spillway Discharges

- Routings of specific frequency floods provides discharges and discharge durations
- Water surface profiles are calculated for discharges obtained from frequency flood routings to provide flow depths and velocities
- Cross waves and air bulking not estimated

Convergence and Divergence of Chute Walls

- Best performance of spillway chute is obtained when confining sidewalls are parallel to the flow direction and flow distribution is uniform
- In order to optimize the spillway design, chute may be narrower or wider than the crest structure or terminal structure
- If convergence is too abrupt, uneven flow distribution and cross waves can develop

Convergence and Divergence of Chute Walls

- Angular variation of flow boundaries should be limited to:

$$\tan\alpha = 1/3F$$

- Froude number:

$$F = v/\sqrt{gd}$$

- α = angular variation of sidewall w/respect to channel centerline

Superelevation of Chute

- Curved spillway chutes result in a rise in water surface on the outside of the chute and a depression of the surface along the inside wall due to centrifugal force
- Rise in water surface for supercritical flow in chutes is about twice that of subcritical flow
- Standing waves can be generated with supercritical flow and simple curves in chute
- For curved chutes with supercritical flow, use of spiral transitions with circular curves and invert banking will reduce the wave heights

Superelevation of Chute

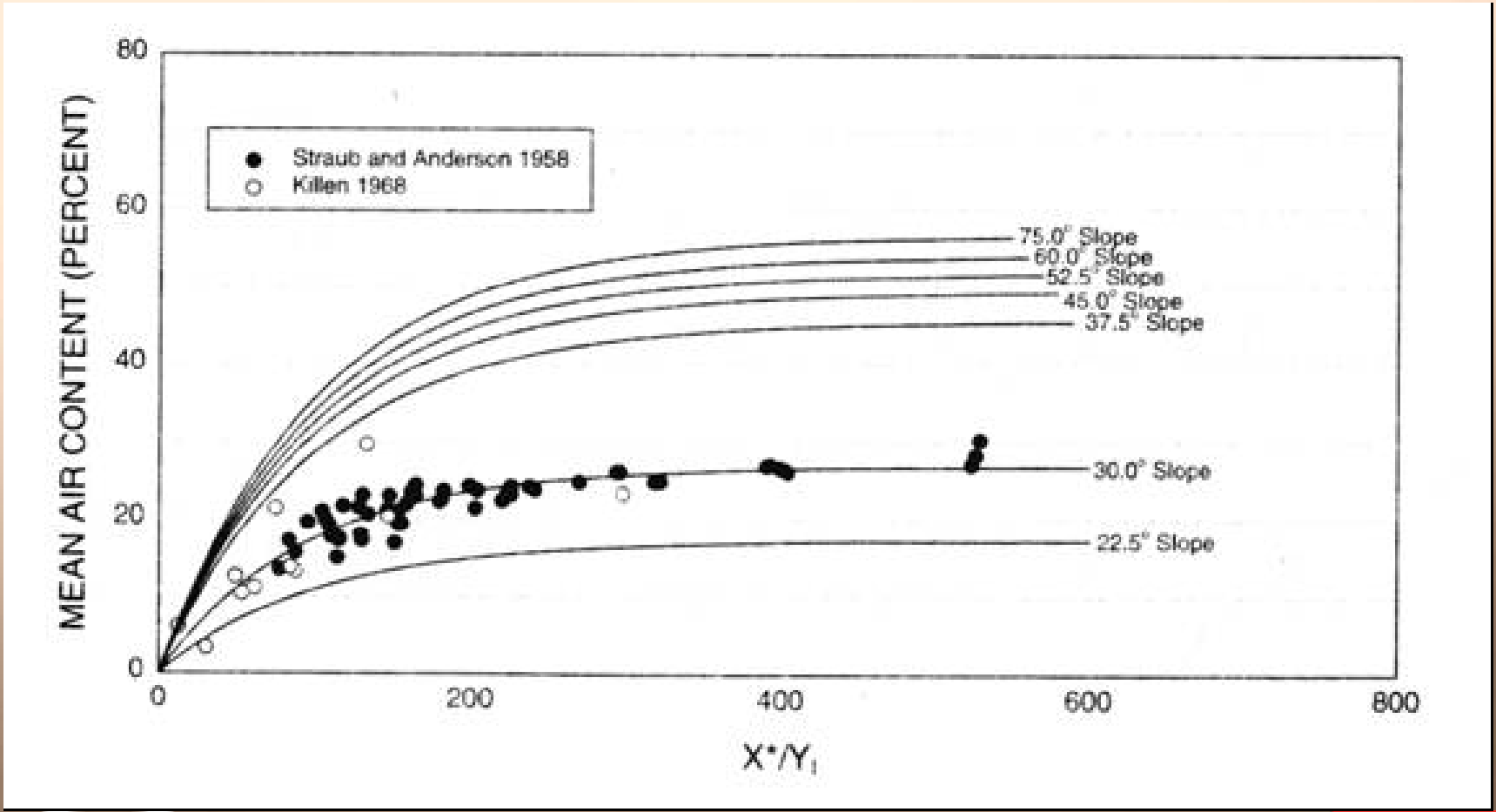
- The following equation provides increase in water surface along outside of curve due superelevation:

$$\Delta y = CV^2W/gr$$

Air Bulking in Flow

- Air bulking will generally increase the depth of flow in chute and is not accounted for in many water surface profile models (ex. ZPROFILE)
- Air bulking occurs where turbulent water boundary layer reaches the water surface and air is introduced into the flow
- $d_b/d = 1/1\text{-}C$

Mean Concentration of Entrained Air (percent by volume) (from Wilhelms and Gulliver, 2005)



Point of Inception

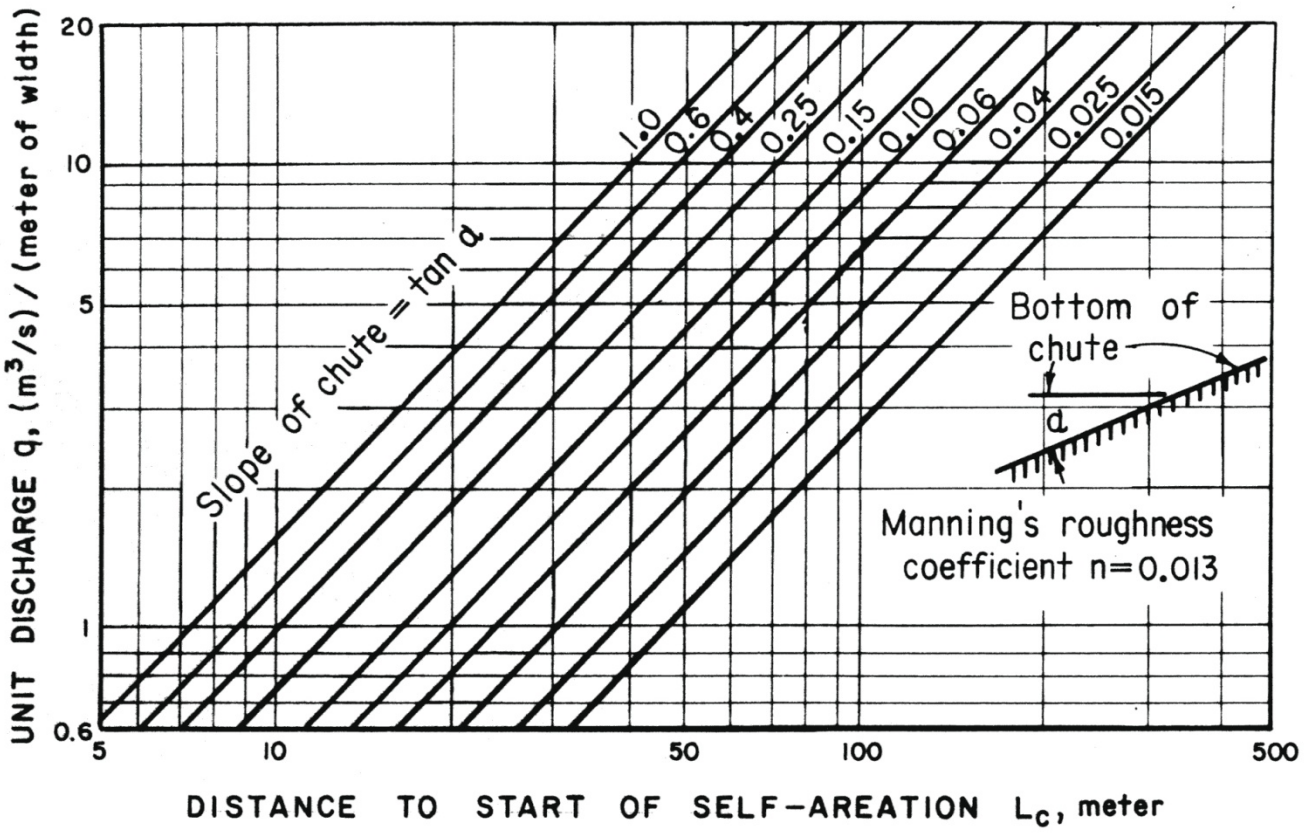
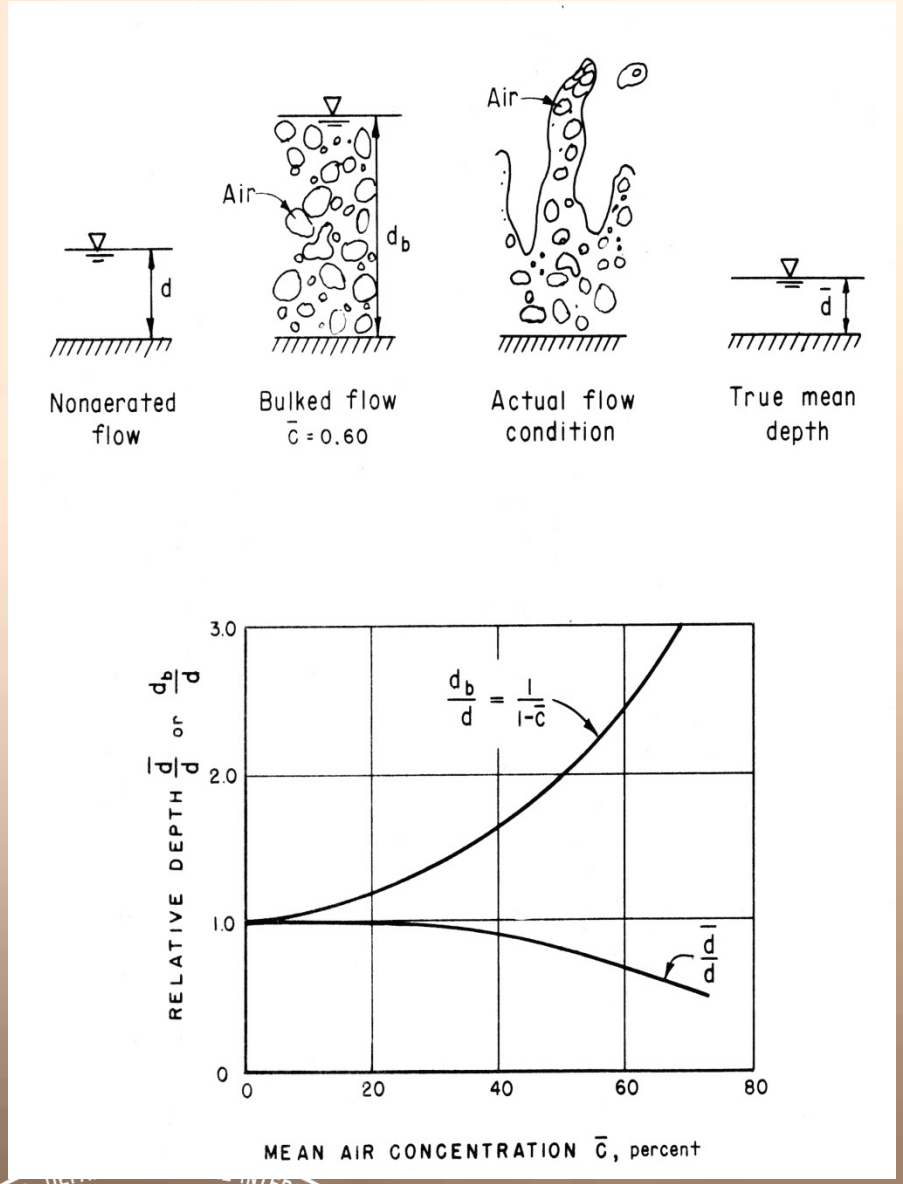


FIGURE 8.—*Location of inception of air entrainment.*

Folsom Dam Spillway

Definitions of aerated flow depths (from Falvey, 1980)



Air Bulking in Flow

- Bulked depth due to entrained air and entrapped air:
- $db/d = 1/1\text{-}(C_e + C_E)$; $C_E = 0.23$
- It has been found that the depth of flow decreases and the velocity increases compared to that calculated from the above equation as air concentration increases above 25 percent due to reduction in coefficient of friction for highly aerated flow

Erodibility of Foundation Materials

- Overtopping flows have the ability to erode backfill, then erode foundation materials, which can lead to undermining of the chute
- Soil foundations are generally more erodible than rock foundations
- Foundation can scour and headcutting can initiate

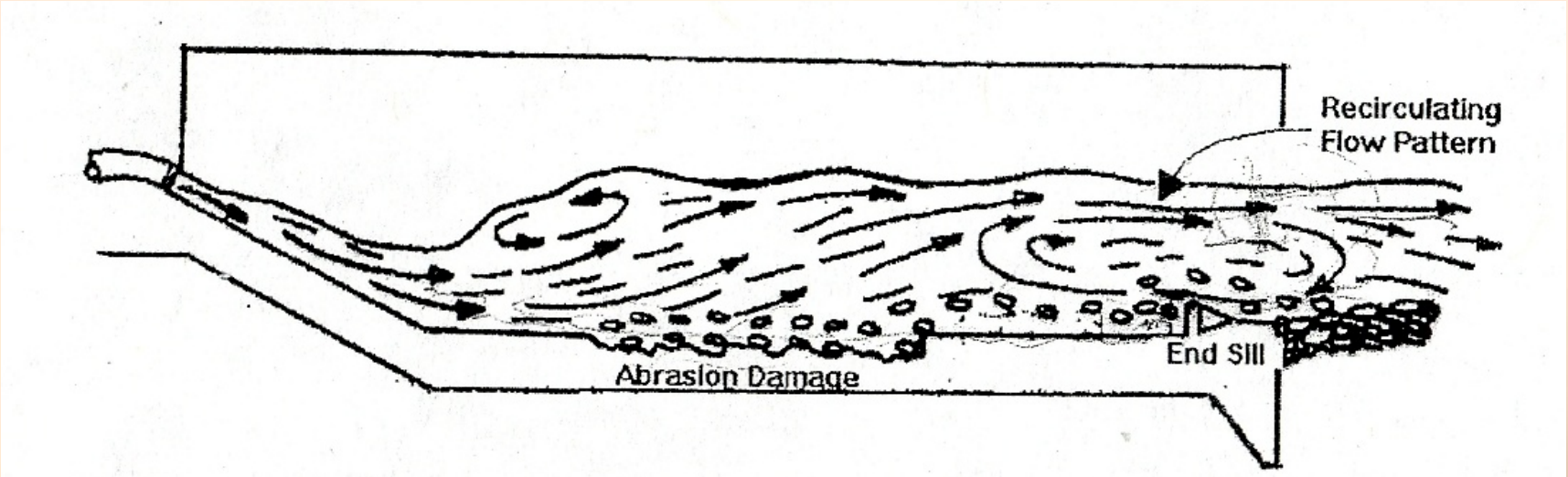
Spillway Configuration

- Uncontrolled spillways are not regulated and provide little or no opportunity to reduce discharges or redirect flows should problems develop during a flood
- Gate spillways may allow for reduction in spillway flows and reliance on reservoir storage space, especially for smaller floods, or brief closure for emergency repairs
- For spillways with multiple gates it may be possible to operate gates to direct flow away from damaged area, at least in upper chute

Ball Milling – Stilling Basin

- Ball milling can expose the spillway foundation and lead to scour and headcutting
- Ball milling is a mechanism where material trapped in a hydraulic jump stilling basin is circulated within the flow and abrades and erodes the stilling basin
- Given enough time, the entire basin floor can be removed, exposing the stilling basin foundation
- Possible to compromise reinforcing steel and destabilize wall

Echo Dam Spillway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Flow Pattern
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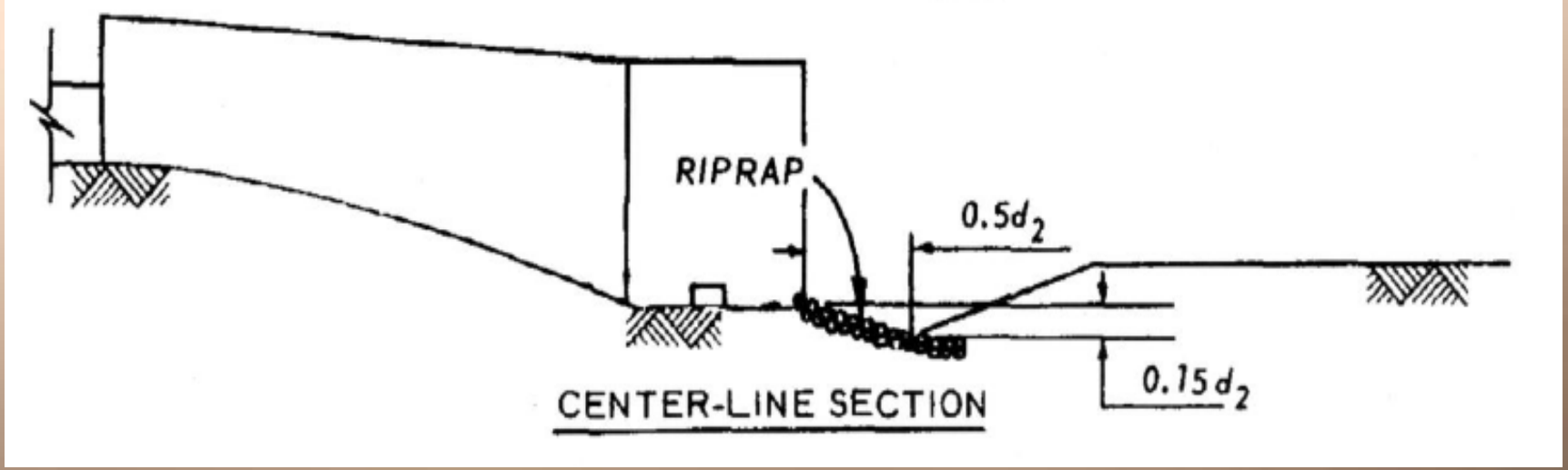
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CENTER-LINE SECTION

Table 24-1 - Ball Milling Case Histories					
Dam	Agency	Concrete Compressive Strength, lb/in^2	Depth of Erosion, in	Duration of Spillway Flows, Days	Abrasion/Erosion Rate in/day
Libby	USACE	5000	24	720	1 inch / 30 days
Dworshak	USACE	n/a	3	53	1 inch / 18 days
Bull Shoals	USACE	3600 (28 day)	18	224	1 inch / 12 days
Pomona	USACE	5000 - 5600	2	960	1 inch / 480 days
Chief Joseph	USACE	n/a	12	420	1 inch / 35 days
Table Rock	USACE	n/a	3	45	1 inch / 15 days
Oologah	USACE	4000 - 5000	17	1100	1 inch / 65 days
Folsom	Reclamation	n/a	30	122	1 inch / 4 days

Stilling Basin Sweepout

- Occurs in hydraulic jump stilling basins
- Tailwater is insufficient to allow the jump to develop or be maintained
- Sweepout can lead to erosion in downstream channel or floatation of stilling basin followed by scour, headcutting and breach
- Evaluate by comparing conjugate depths for various flows to predicted tailwater elevation

Hydraulic Jump Stilling Basin

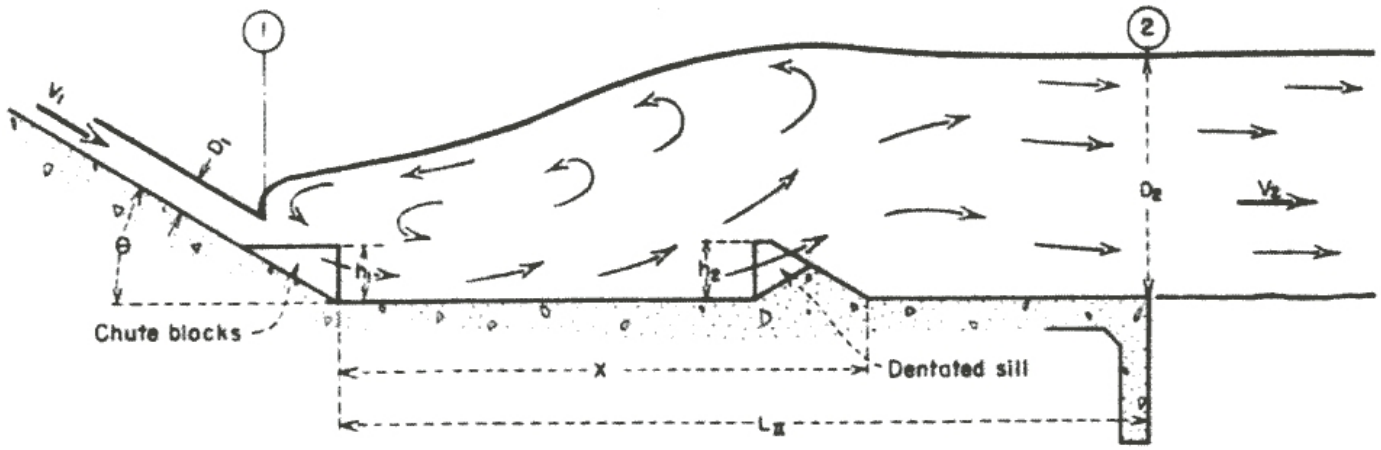


FIGURE 10.—*Definition of symbols (Basin II).*

Wall Overtopping Event Tree

- 1. Starting Res Elev
- 2. Flood Load Range
- 3. Spillway Flows OT Chute Walls
- 4. Erosion Initiates in Spillway Backfill
- 5. Chute Undermined
- 6. Headcut Initiates
- 7. Unsuccessful Intervention
- 8. Breach Forms

Failure of El Guapo Dam

- El Guapo Dam spillway failed 12/16/99 as a result of chute wall overtopping
- El Guapo Dam never overtopped
- Overtopping of chute walls initiated erosion of backfill behind chute walls and undermining and failure of spillway chute
- Headcutting progressed upstream and lead to reservoir breach
- Spillway foundation consisted of decomposed rock, which was erodible

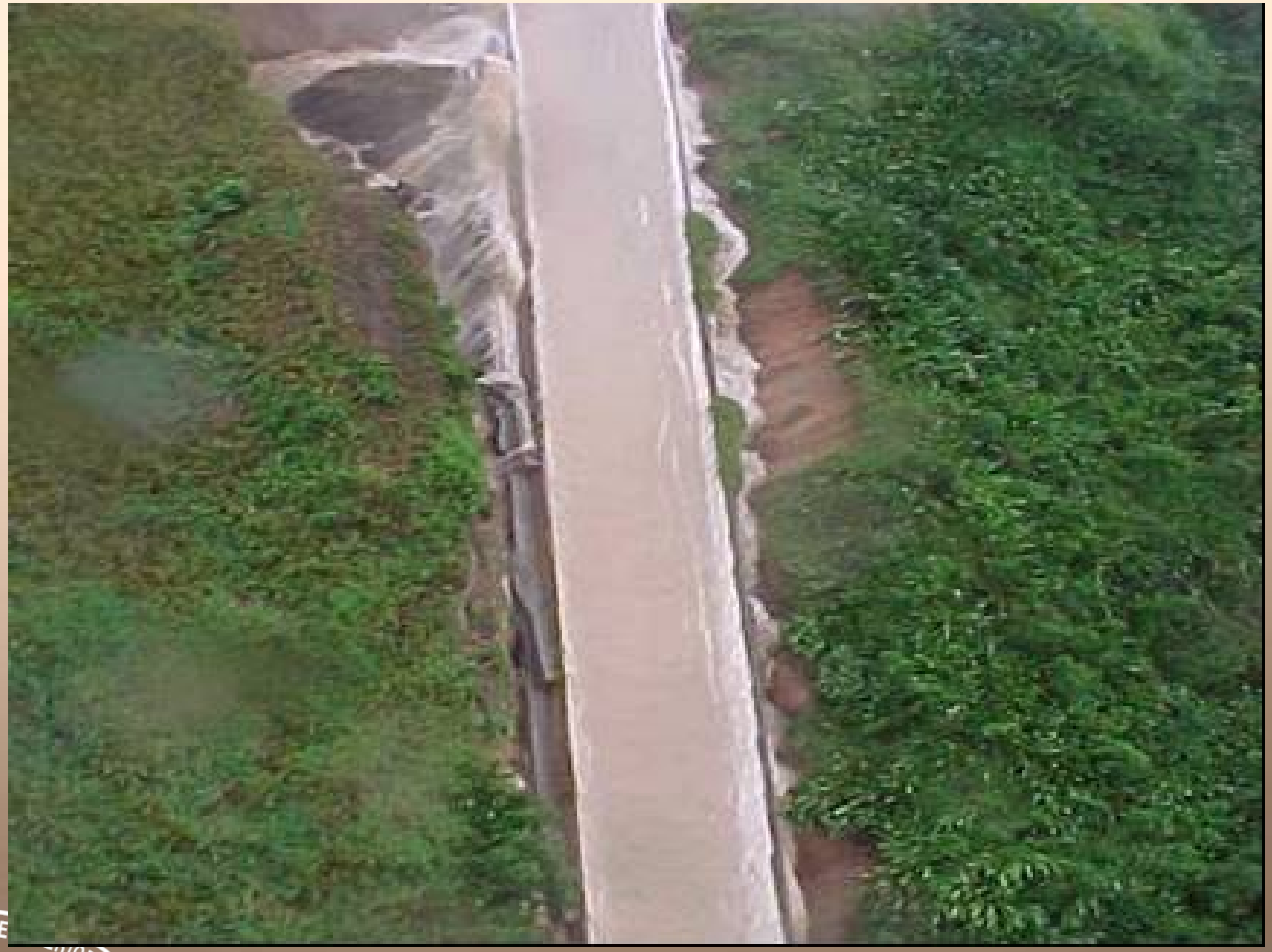
Approach Channel to Spillway

Spillway Chute

Sweepout of spillway stilling basin

Overtopping Along Entire Length of Chute

Overtopping of Upstream Chute Walls



Breach Formation Nearing Completion

Headcutting Progressed to Reservoir

Aftermath of Reservoir Breach