Hydraulic Jacking

Best Practices in Dam and Levee Safety Risk Analysis

Part F – Hydraulic Structures

Chapter F-1

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Outline

- Two Main Types of Hydraulic Jacking
- Case Histories
- Typical Event Trees
- Key Considerations
- Analytical Methods
- Defensive Measures

Objectives

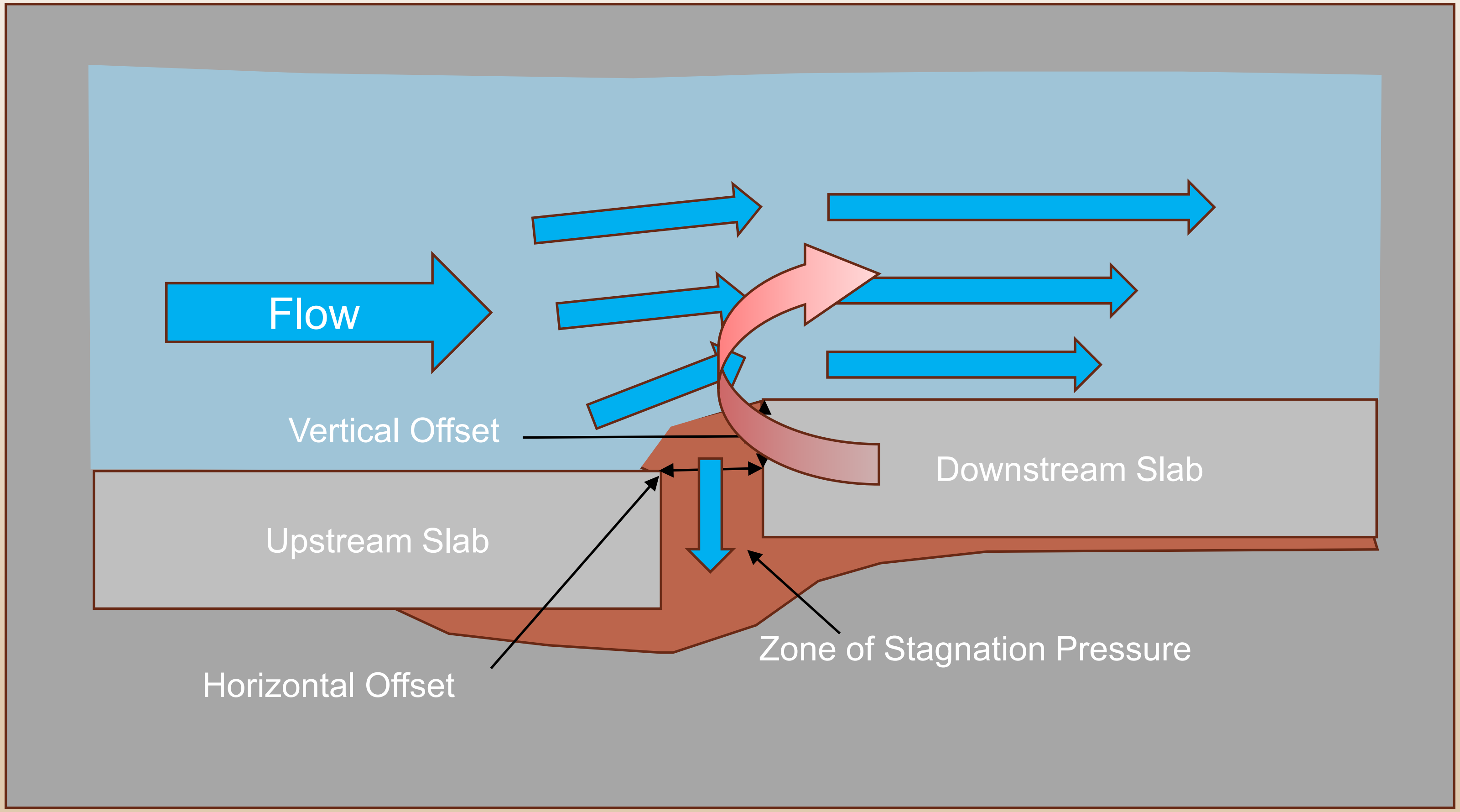
- Understand the mechanisms that affect the vulnerability of spillway chute and stilling basin slabs to hydraulic jacking
- Understand how to construct an event tree to represent the hydraulic jacking leading to failure
- Understand how to estimate potential for hydraulic jacking and understand the progression mechanism to failure

Key Concepts

- Hydraulic Jacking can occur through two main mechanisms, stagnation pressures and extreme pressure fluctuations
- Hydraulic Jacking of Spillway Chute/Stilling Basin Slabs has occurred at several large dams
  - Resulted in significant damage that led to the initiation of some potential failure modes
  - Many hydraulic structures for large federal dams were constructed prior to a thorough understanding of these vulnerabilities
- There are very effective design details that can reduce the probability of this failure mode initiating

Two Main Types of Hydraulic Jacking

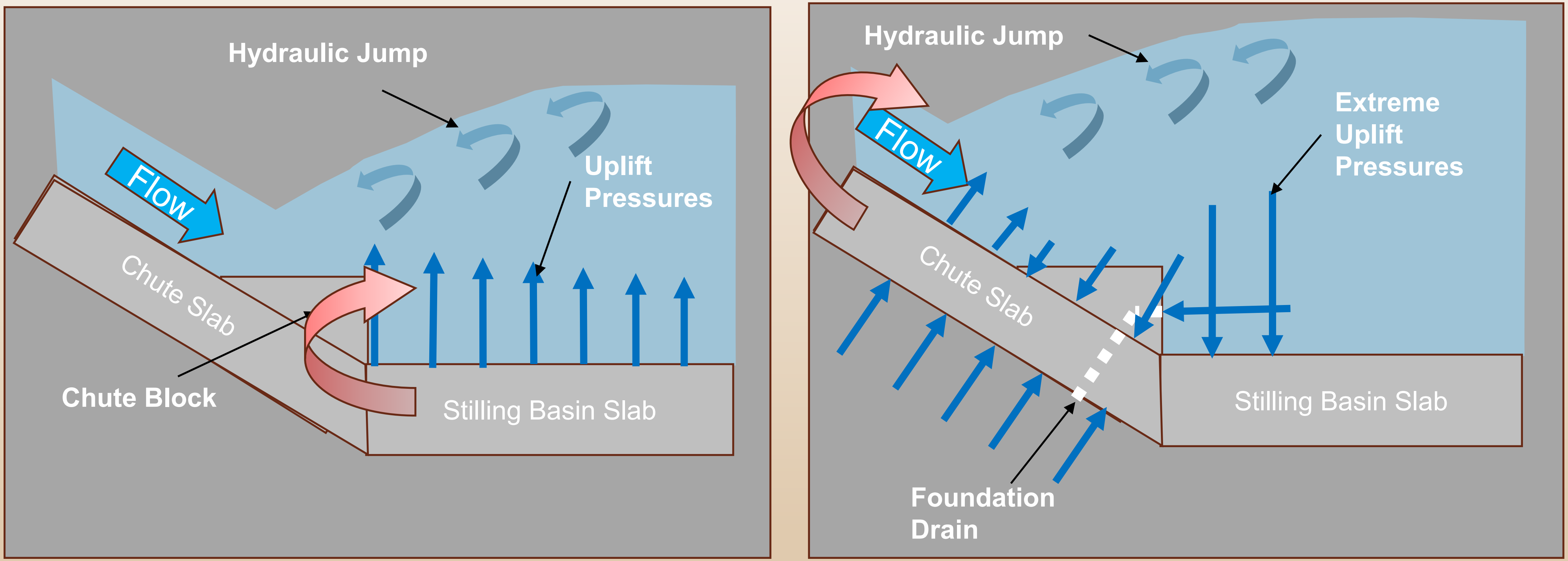
Stagnation Pressures



Stagnation Pressure Initiation

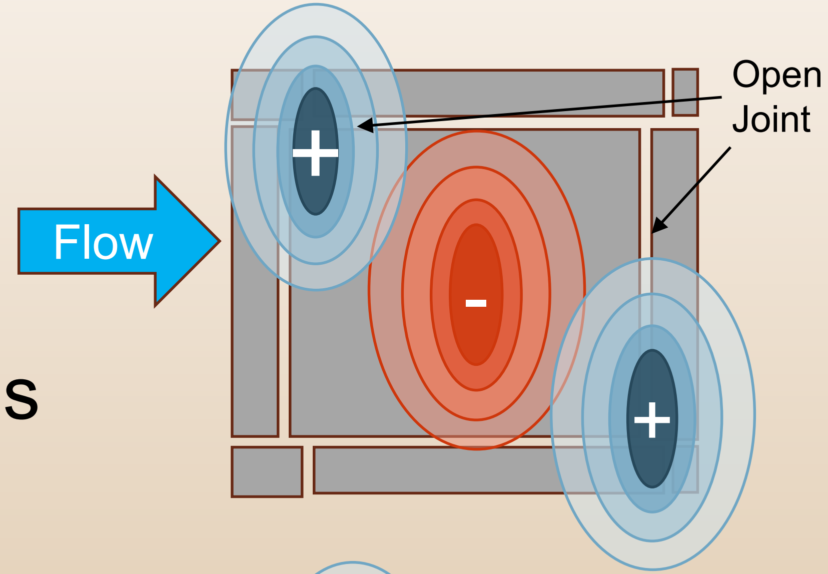
- Stagnation pressure enters joint and reaches foundation – High pressures/Significant flows
- Limited/Blocked Drainage Capacity
  - Pressures develop that exceed weight/anchorage
  - Hydraulic jacking removed slab
- Drainage
  - Erosion of foundation materials due to the introduction of spillway flows underneath the spillway chute
  - Collapse of structure

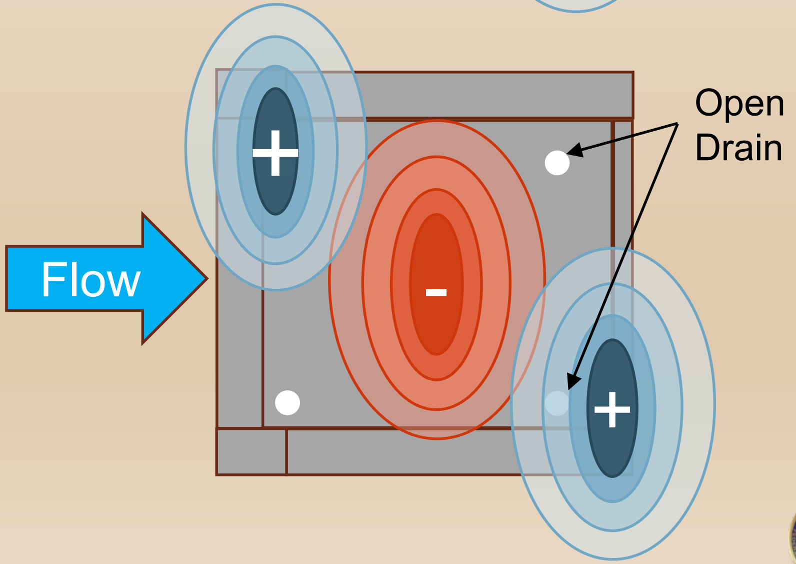
Extreme Pressure Fluctuations



Fluctuating Pressure Failure Initiation

- Hydraulic jump creates high pressure fluctuations that can act in different directions across the jump
- Negative pressures can occur over the slab at the same time positive pressures can charge under the open slab thru joints and foundation drains
- The location of the hydraulic jump can move with changing flow conditions and tailwater and create unexpected combinations





Case Histories

Causes of Offsets in Chutes and Basins

Geology/Foundation

- Rebound or swelling of soils or shales
- Shears, faults, stress relief, gas/oil extraction

Structural

- Spalling, ASR, poor joint details, ice damage in joints
- Cracking due to poor details such as drains projecting into section

Slab Stability

- Failed anchors due to pull out
- Unfiltered drains resulting in erosion of foundation soils

Others

- Frost, tree roots plugging drains, ice lenses beneath slab

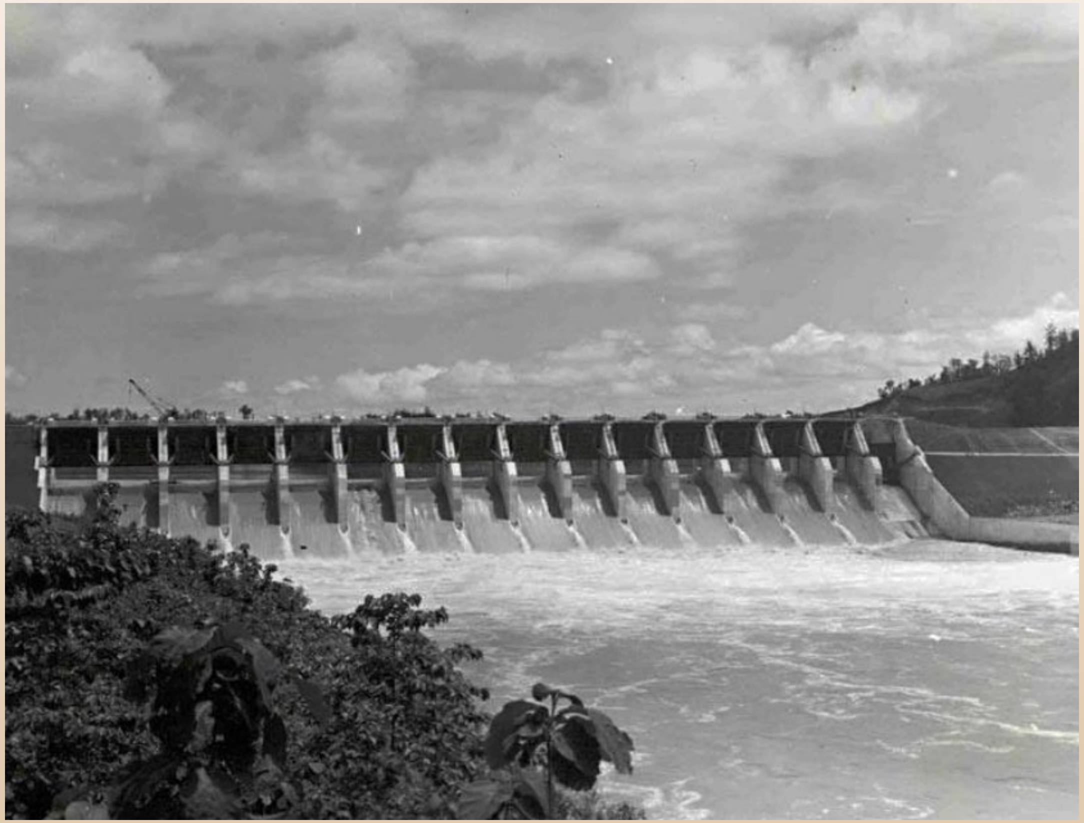
Big Sandy Dam

- USBR Dam in Wyoming
- 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 Dam

- Big Sandy Spillway Slab failed during spillway discharge of 400 ft^3/s
- Failure was initiated by offset into flow (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
- Analysis demonstrates that with anchor bars fully effective, slab would not have failed by Stagnation Alone
- From observations after failure, anchor bars exposed beneath slab were not coated with grout which suggests they were not bonded

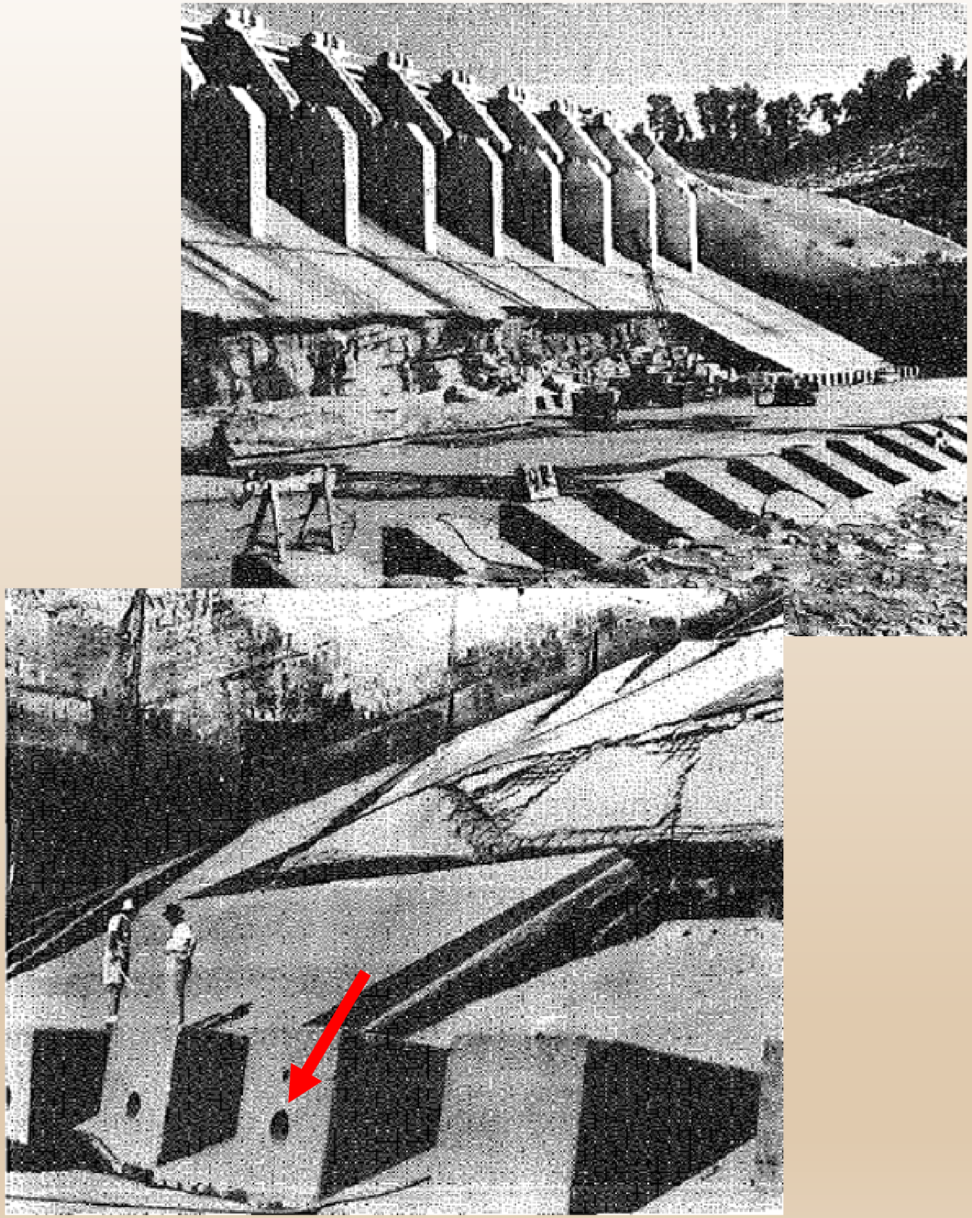
Karnafuli Case History



- Project is located in Bangladesh
- Spillway operated immediately after completion in 1961 during a Monsoon Flood
- Distressed areas were observed on August 13th; but project continued to flow until August 20th
- Inspection after the event demonstrated significant damage to the lower spillway chute slabs
- Slabs were 1.5-ft to 4-ft thick, underlain with sand and chute blocks that have foundation drain exits

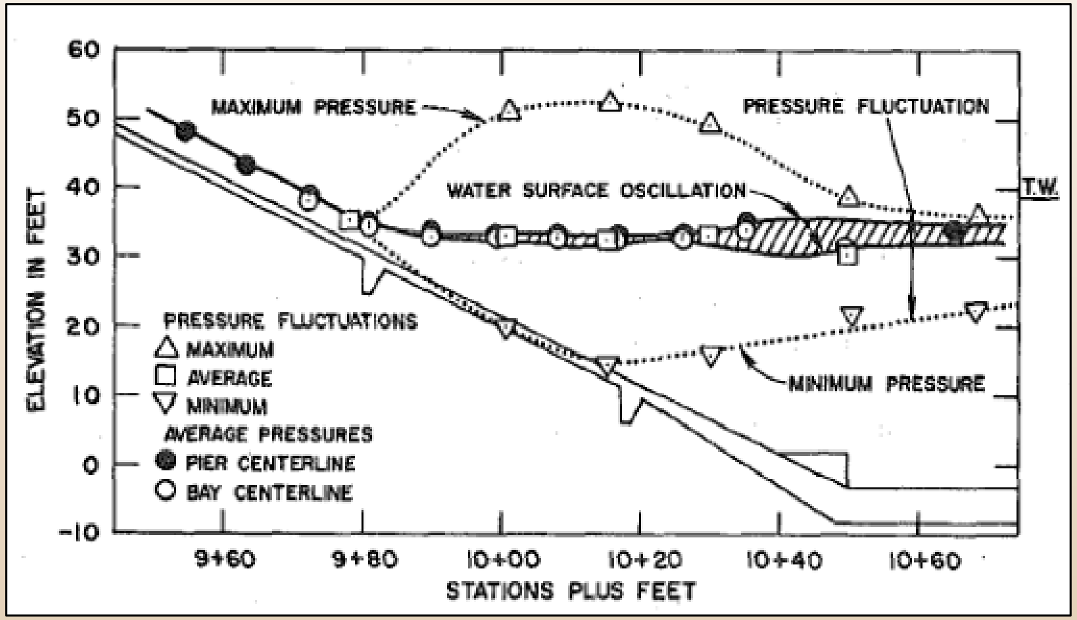
Karnafuli Case History

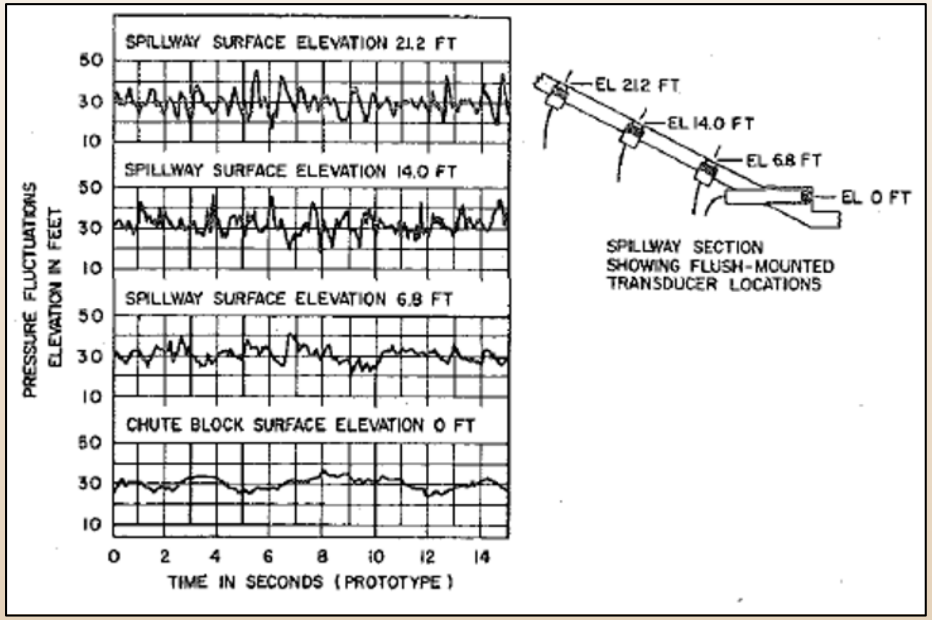
- There was damage to approximately 600-ft of the 745-ft wide spillway chute
- Significant erosion of exposed rock
- Board of Consultants concluded that the failure was a result of fluctuating pressure near the toe of the hydraulic jump
- Physical modeling suggests that it was likely that low pressures occurred over the slab while simultaneously positive pressures charged the foundation
- Design philosophy at the time was that the back of the Chute Block would be low pressure zone, the actual tailwater was higher than assumed for design, forcing the jump on the chute

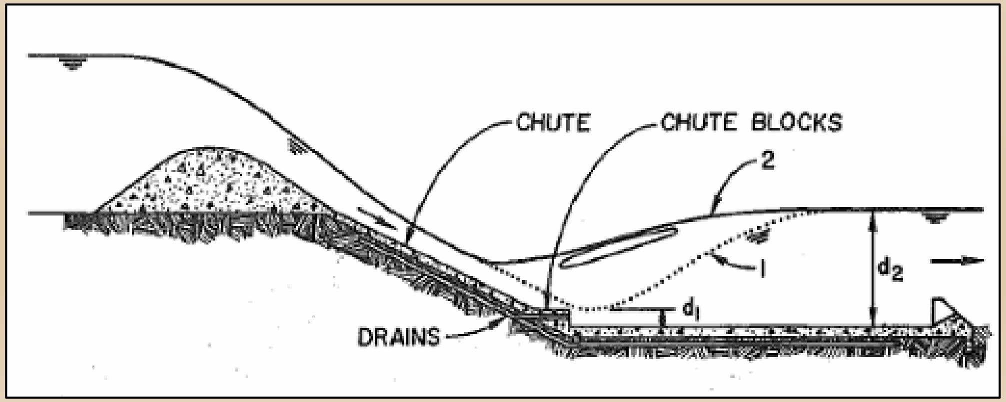


Photos from Bowers et al 1988

Karnafuli Case History

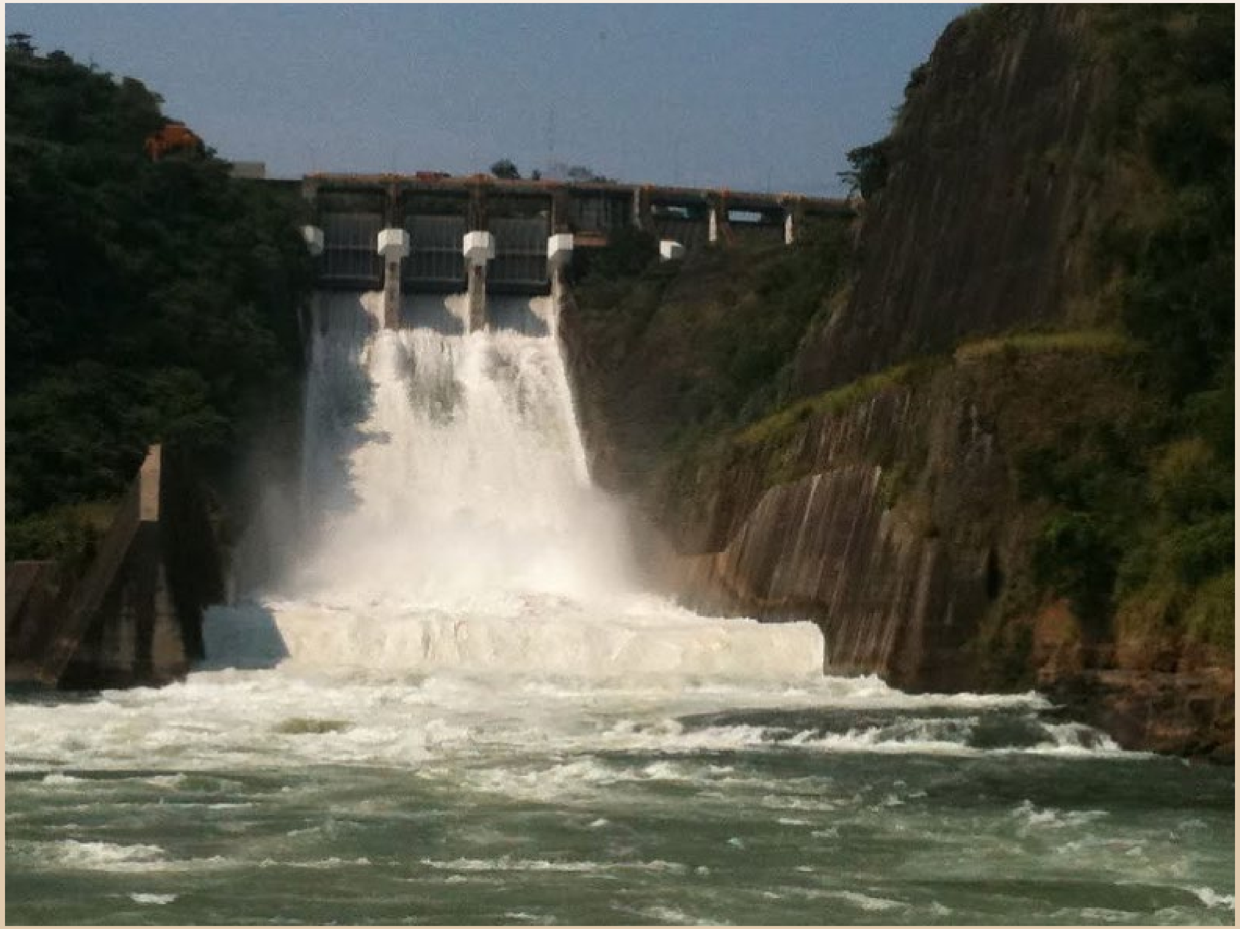






St Anthony Falls Hydraulic Laboratory, Project Report No. 73, Hydraulic Studies of the Spillway of the Karnafuli Hydroelectric Project East Pakistan

Malpaso Case History



- 450 foot high Embankment Dam in Mexico
- 8.5 million acre-feet reservoir
- 320-foot Long, 160-foot wide hydraulic jump stilling basin
- Design Discharge of 212 kcfs
- Operated for three years at flows below 88 kcfs
- Had severe stilling basin damage after a 106 kcfs flow event

Malpaso Case History

- Multiple Slabs Failed
  - 40ft x 40ft in size
  - 6.5 ft thick
  - (12) 1 ¼ inch bars in each slab
- Slabs flipped upside down and deposited at exit channel
- Significant damage to exposed rock
- Slab failure was attributed to Hydraulic Jacking related to fluctuating Pressures

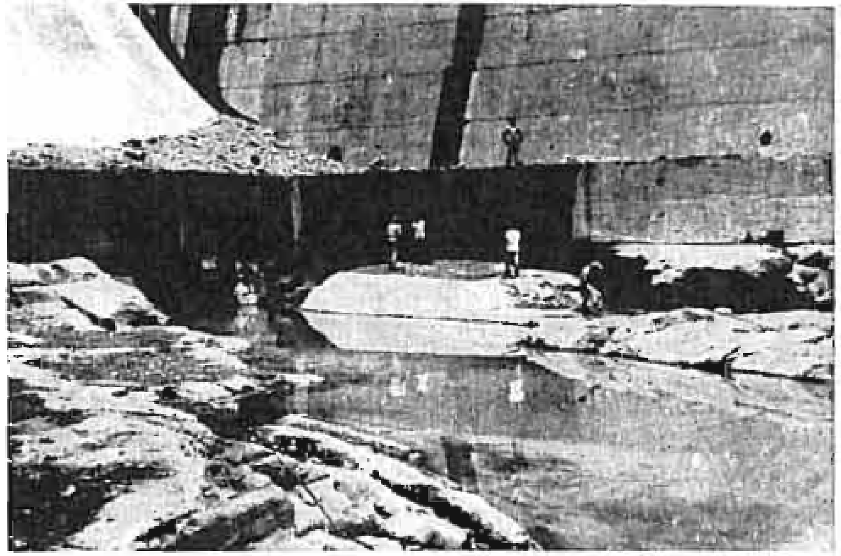


Plate 1
View of stilling basin damages.

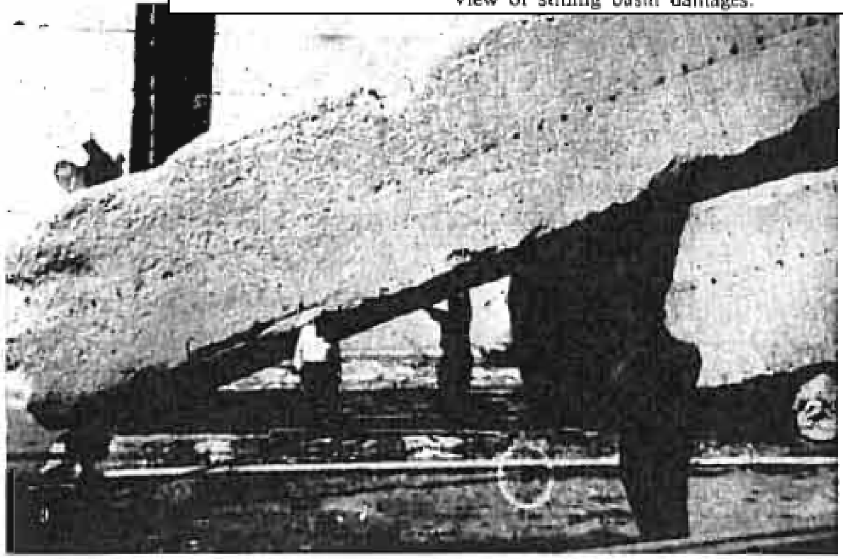


Plate 2
Another aspect of damages.

Hyrum Case History

- USBR Dam located in Utah
- 116 feet high earthfill embankment completed in 1935
- Thin concrete-lined spillway chute
- Erodible foundation soils

Hyrum Case History

- A continuous channel over two feet deep in places was observed
- No steel across the slab joints
- Underdrain system; but no filter

Typical Event Tree

Typical Event Tree for Stagnation Pressures

- Flows of Sufficient Velocity to Displace Slab Occurs
  - Unfavorable Open Joint Offset Exists
    - Defense Measures for Joints are Ineffective
      - Structural Slab Failure
        - Head Cut Initiates
          - Head Cut Progresses to Breach

Typical Event Tree for Fluctuating Pressures

- Flows of Sufficient Velocity to Create Pressure Fluctuations Required to Displace Slab
  - Open Joint or Drain in Stilling Basin Exists
    - Defense Measures for Joints are Ineffective
      - Structural Slab Failure
        - Head Cut Initiates
          - Head Cut Progresses to Breach

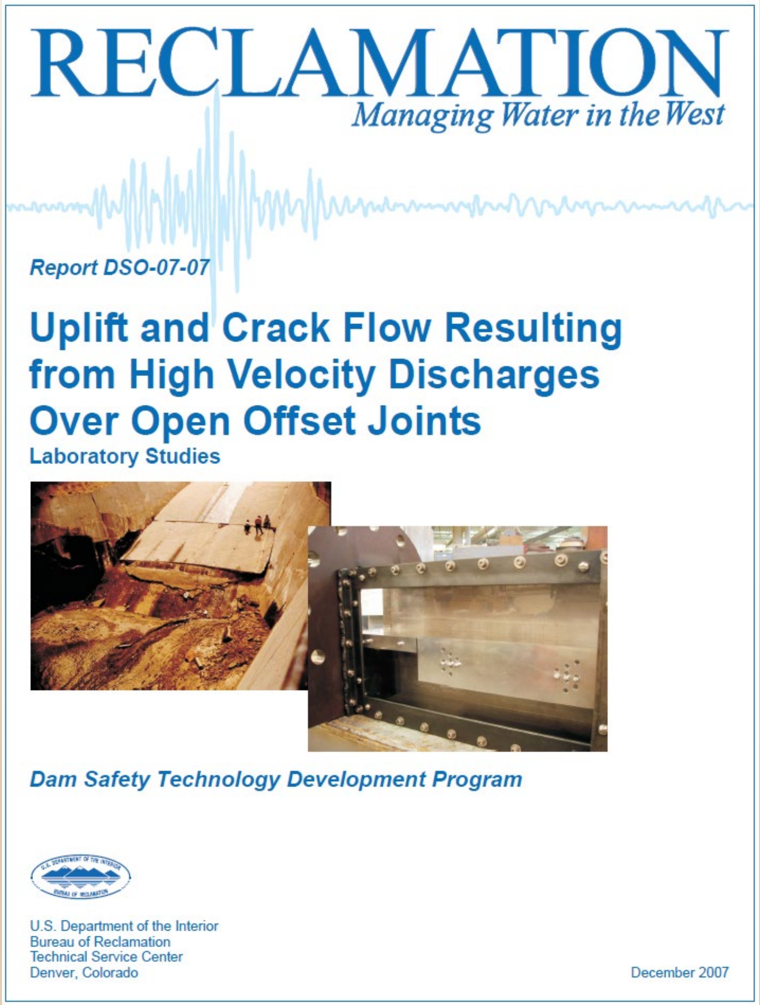
Key Considerations

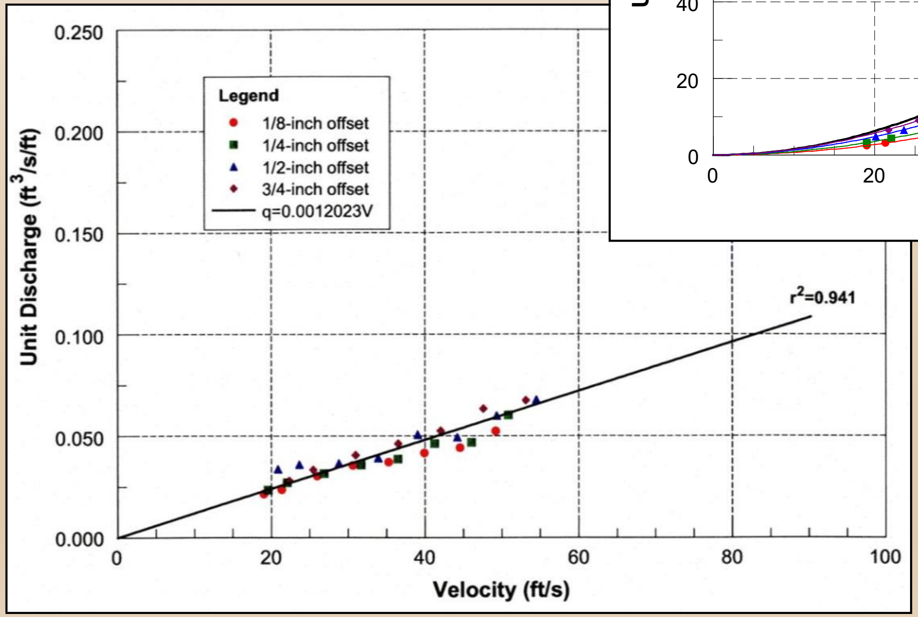
Key Considerations

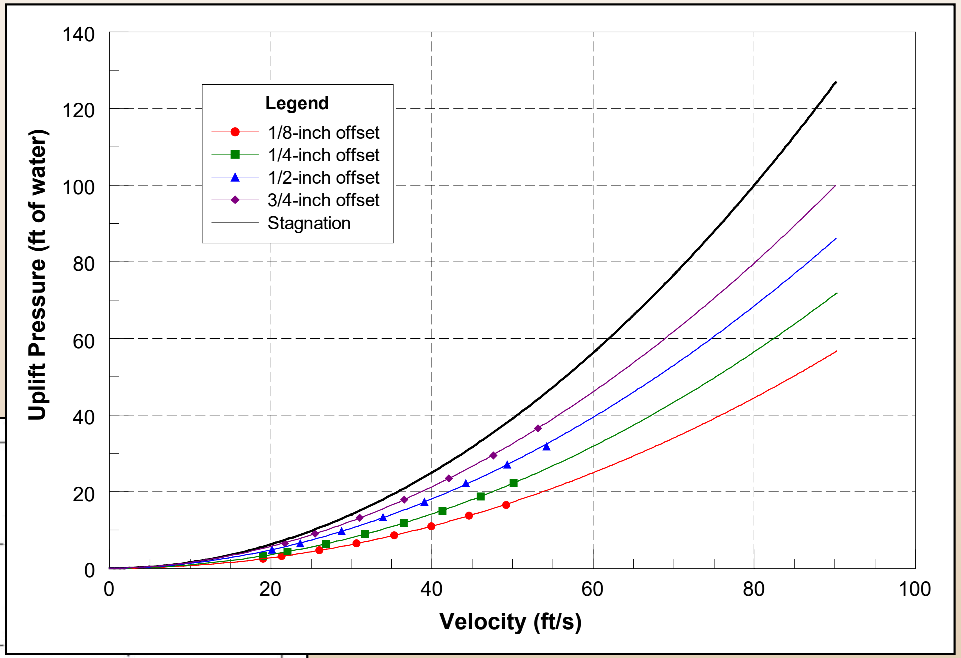
- Is there sufficient velocity head to dislocate slabs?
- Do we know the location of the hydraulic jump over the range of flow conditions?
- Is there a potential for vertical offset into flow?
- Are the foundation materials erodible?
- If a slab fails, is there a potential for progression to breach?
- Is there continuous reinforcement across joints?
- Are there reliable water stops?
- Is there an underdrainage system to prevent uplift buildup in the case of stagnation pressure?
- Is the spillway gated - for potential intervention?

Analysis Methods

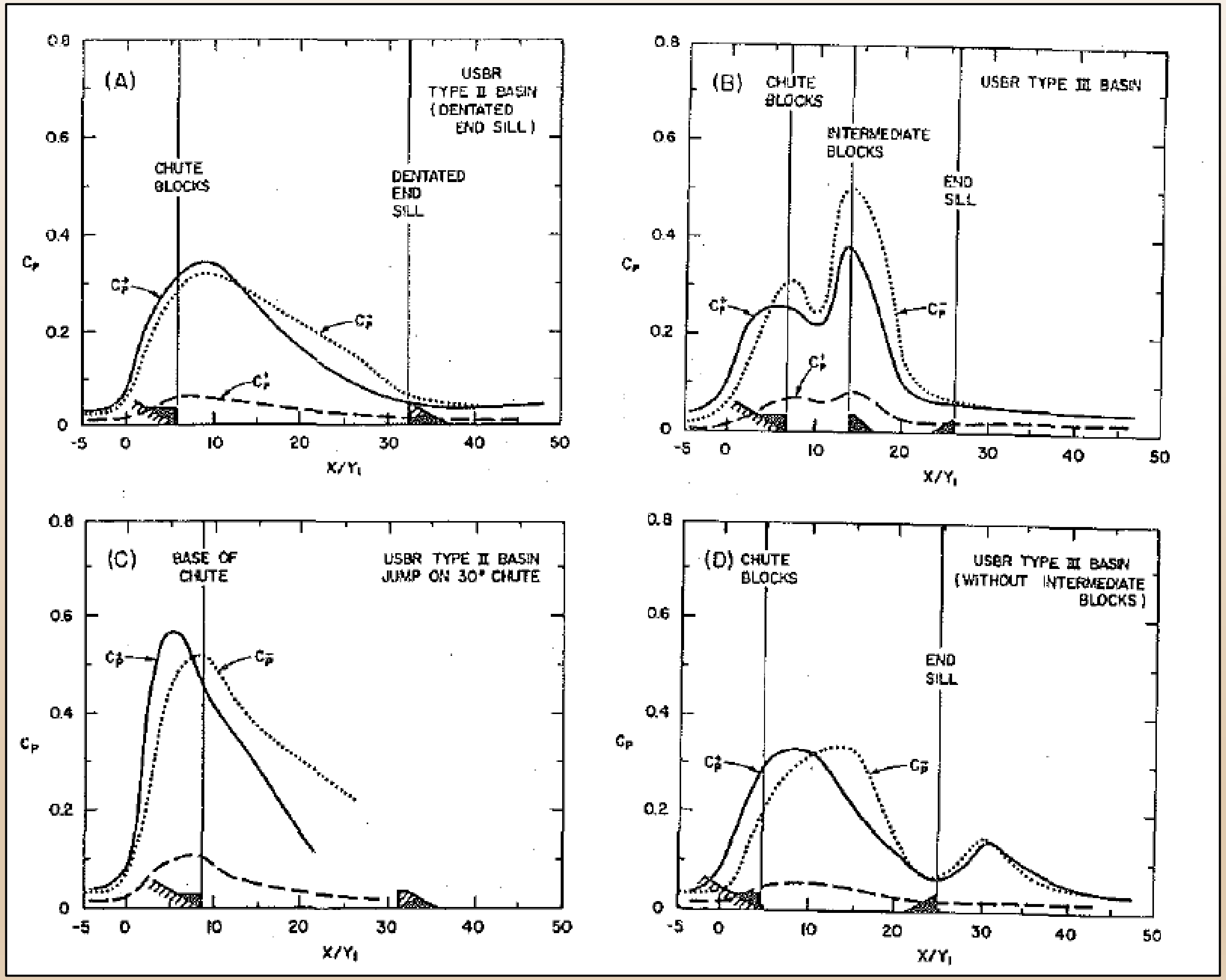
Analysis Methods (Stagnation Pressures)



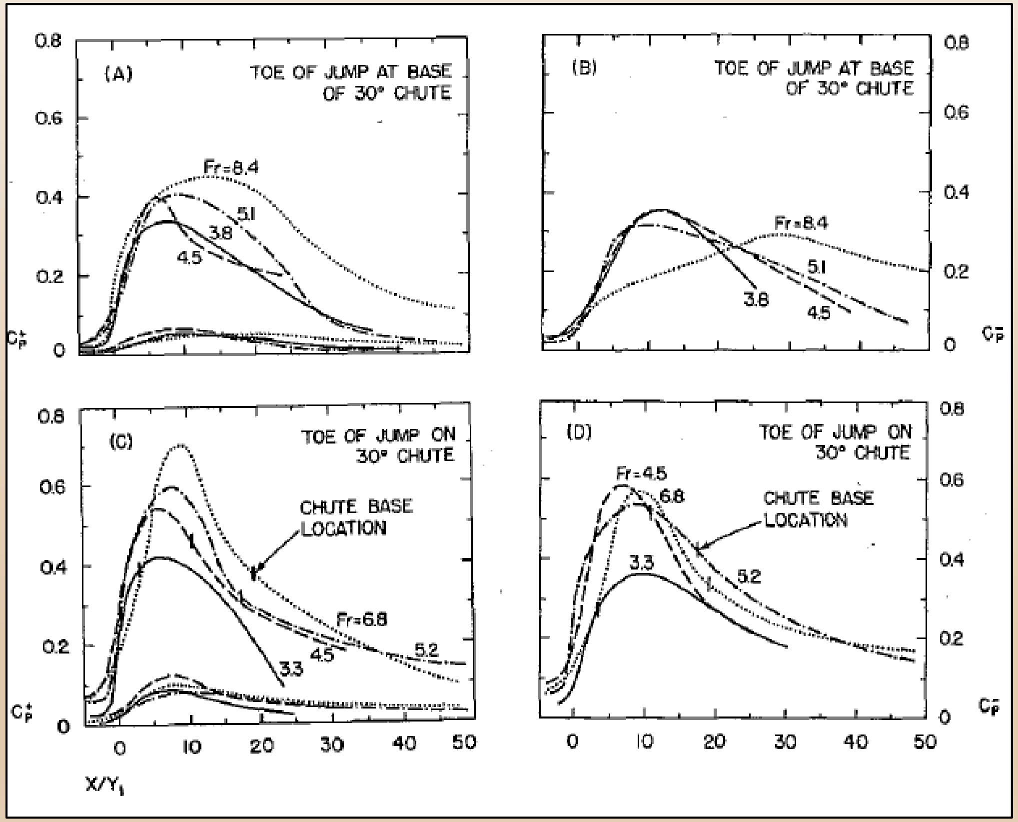




Analysis Methods (Pressure Fluctuation)



$$\Delta P = C_p^{+/-} * \frac{V^2}{2g}$$



Toso and Bowers (1988)

Defensive Measures

Defensive Measures – Stagnation Pressures

Evaluate the presence and effectiveness of these design details when assessing risk:

- 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 Measures – Fluctuating Pressures

Evaluate the presence and effectiveness of these design details when assessing risk:

- Waterstops – prevent flow through joints
- Joint Reinforcement – minimize width of cracks/joint openings, helps prevent water stop failure, and creates a larger component to resists localized instantaneous pressures
- Anchor bars – provides resistance to fluctuating pressures
- Drain Location – Avoid drains located in the area of the hydraulic jump (especially in the toe of the jump or upstream of baffles)

Takeaway Points

- Hydraulic Jacking has occurred in multiple projects due to stagnation and fluctuating pressure
- Hydraulic Jacking of a Slab is only the initiation of the PFM (Crosswalk with Erosion of Rock and Soil)
- Major vulnerabilities exist when:
  - Open gaps in transverse chute slab joints with an offset into flow exist
  - Open joints or drains in the location of hydraulic jumps exist
  - Dynamic hydraulic loads are not included in design considerations

Questions or Comments?

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