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Managing Water in the West

Incorporating Breach Parameter Estimation and Physically-Based Dam Breach Modeling into Probabilistic Dam Failure Analysis

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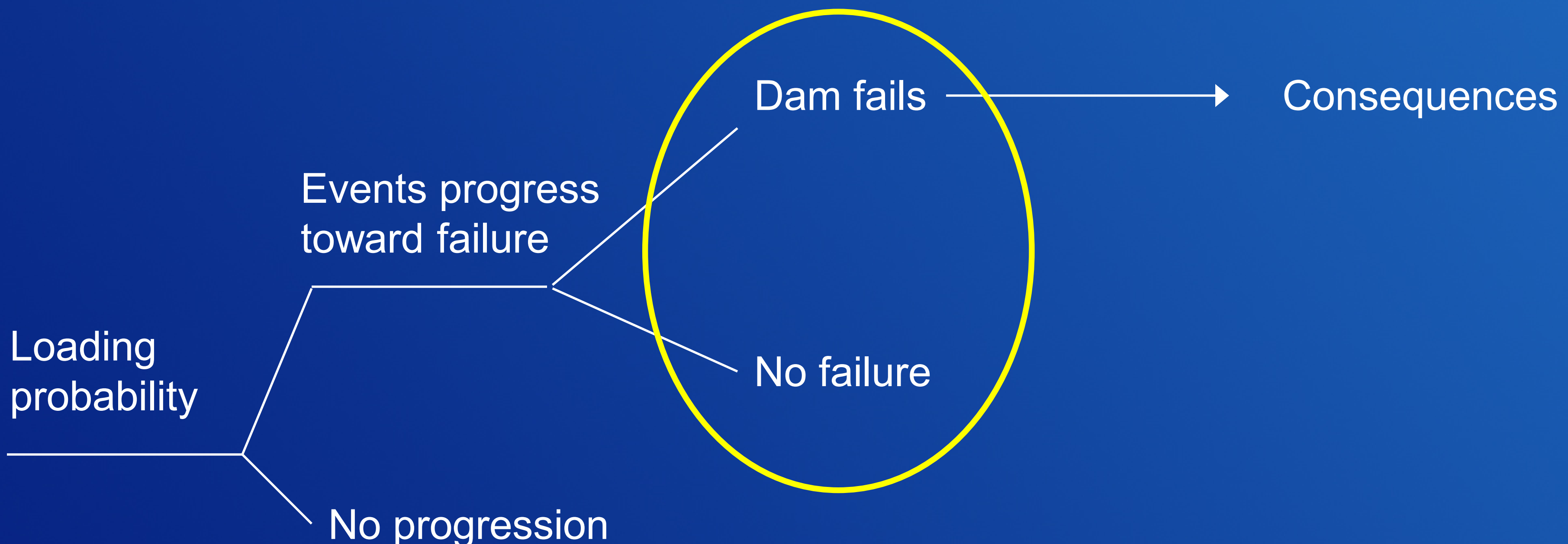
Issues

- How to evaluate failure probability?
- How to estimate breach parameters in a probabilistic way?
  - Size of breach
  - Shape of breach
  - Time of failure (rate of erosion)
- Scope of this talk limited to embankment dams

Failure Probability

- **Failure probability is a central question**



Hydrologic Failure Modes

- Is depth and duration of overtopping sufficient to produce unstoppable erosion?
- Can flood surcharge in the reservoir trigger a seepage-erosion sequence that progresses too quickly to stop?

Riley 1986

- First work discussing analysis of limited overtopping that might not cause dam failure
- Applied only to cohesive, erosion-resistant embankments protected by well maintained vegetation
- Suggested permissible duration-velocity limits for flow over crest and down the slope
- Also suggested permissible total volumes of flow in a given duration

Riley 1986

- Addressed the “will it fail?” question
  - Suggested conservative thresholds for when failure would occur
- Did not address the probability of failure question
  - When thresholds were exceeded, probability of failure was 1

Fragility Curves

- Attempt to estimate probability of failure <u>based on engineering judgment of team members</u>
  - Depth of overtopping
  - Velocity of flow
  - Duration of overtopping / Volume of water
  - Quality of slope protection (vegetation or riprap)
  - Erodibility of embankment materials
- Very subjective…

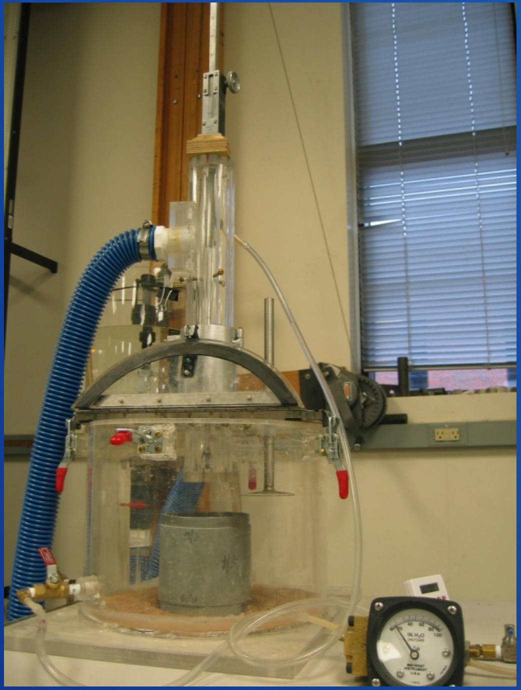
New Tools

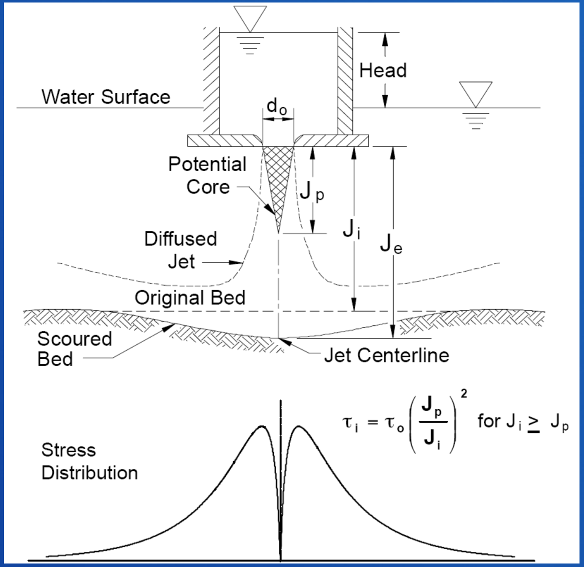
- Physically-based dam breach models
  - WinDAM (USDA-ARS)
  - HR BREACH (HR Wallingford)
  - Others…

Dam Breach Models

- Inputs
  - Hydraulic attack (overtopping depth, velocity, shear stress, stream power)
  - Slope protection, threshold of failure
  - Erodibility of embankment material (measured!)
    - Estimate erosion rates
    - Simulate mechanics of headcut development
  - Simulate extent of erosion during duration of event

Submerged Jet Test - Erodibility





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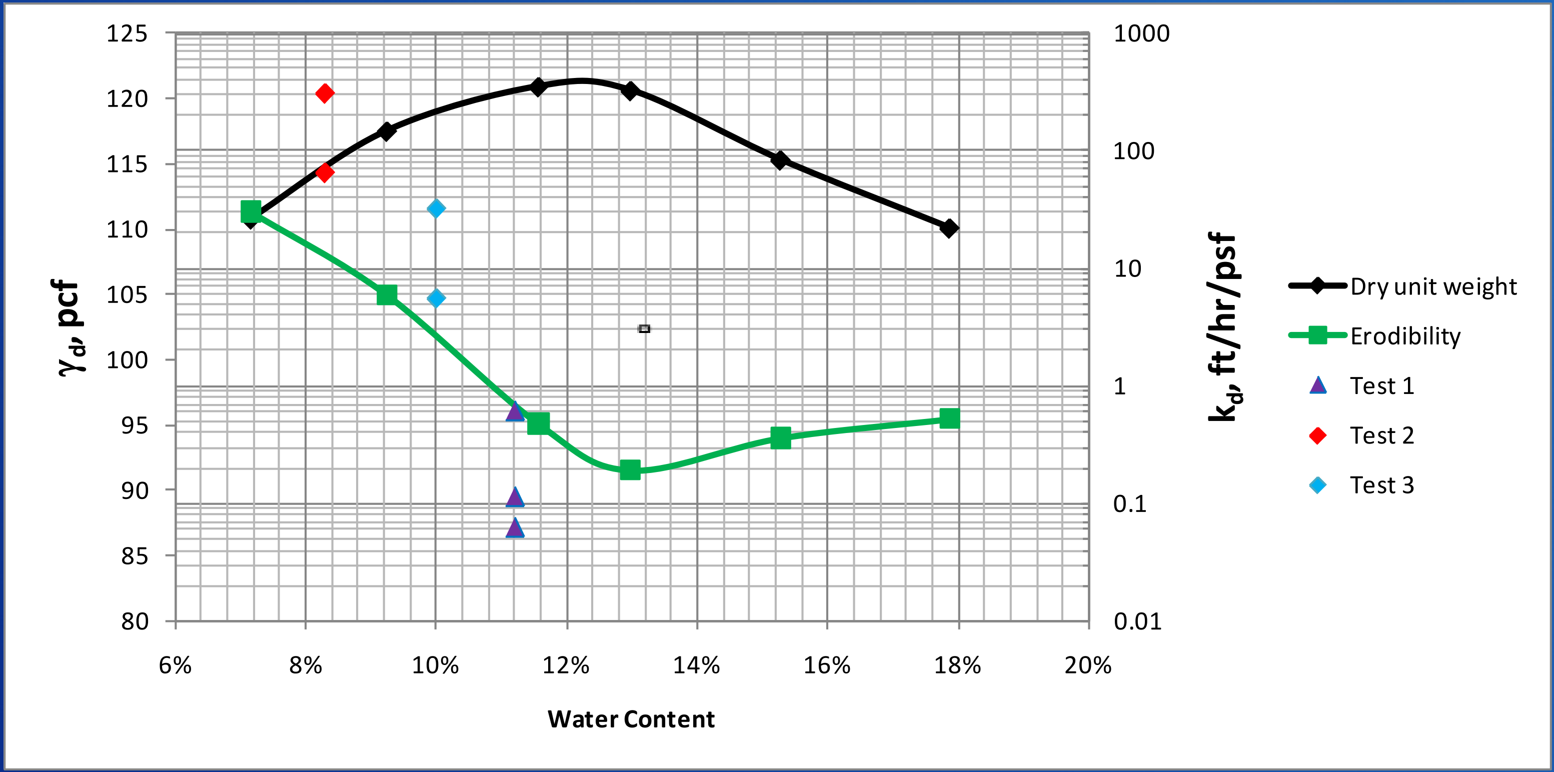
Compaction & Erodibility



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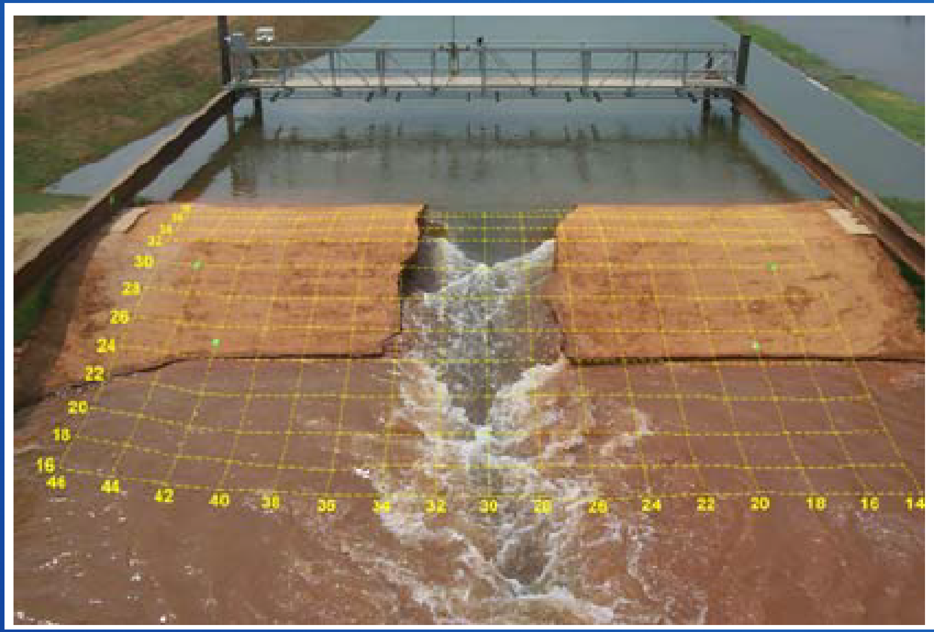
Dam Breach Models

- Output
  - Determine whether threshold for failure is reached
  - Outflow hydrograph
  - Time-history of breach development

  → Consequence analysis

- Probabilistic uses
  - Models run quickly
  - Can readily analyze variations in flood loading, slope protection and soil erodibility

Greg Hanson and Sherry Hunt – USDA-ARS



Soils used in breach widening tests

Soil	Sand[1] > 75μm (%)	Fines[1] > 2μm (%)	Fines[1] <2μm (%)	PI[2]	Soil Classification[1]
2	63	31	6	NP	SM-Silty Sand
3	25	49	26	17	CL-Lean Clay

Effect of Wet or Dry Compaction is Dramatic

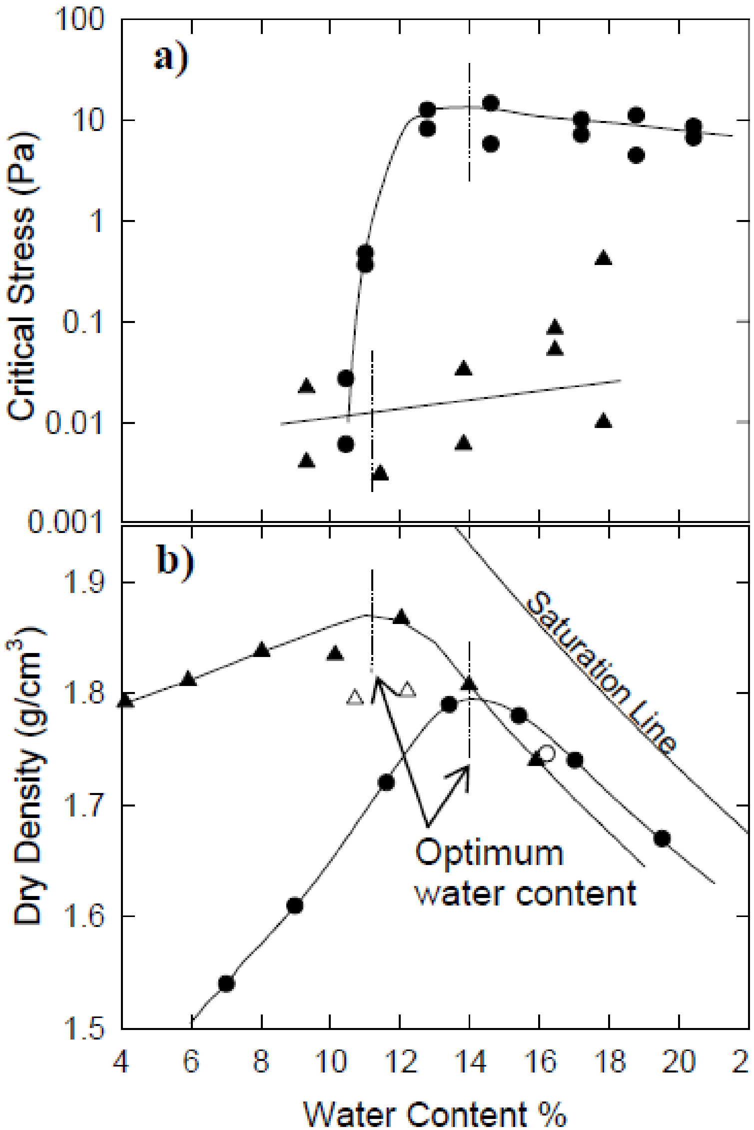


Figure 6. a) Critical stress, τ_c vs. water content for Soil 2 and Soil 3, b) Dry density vs water content.

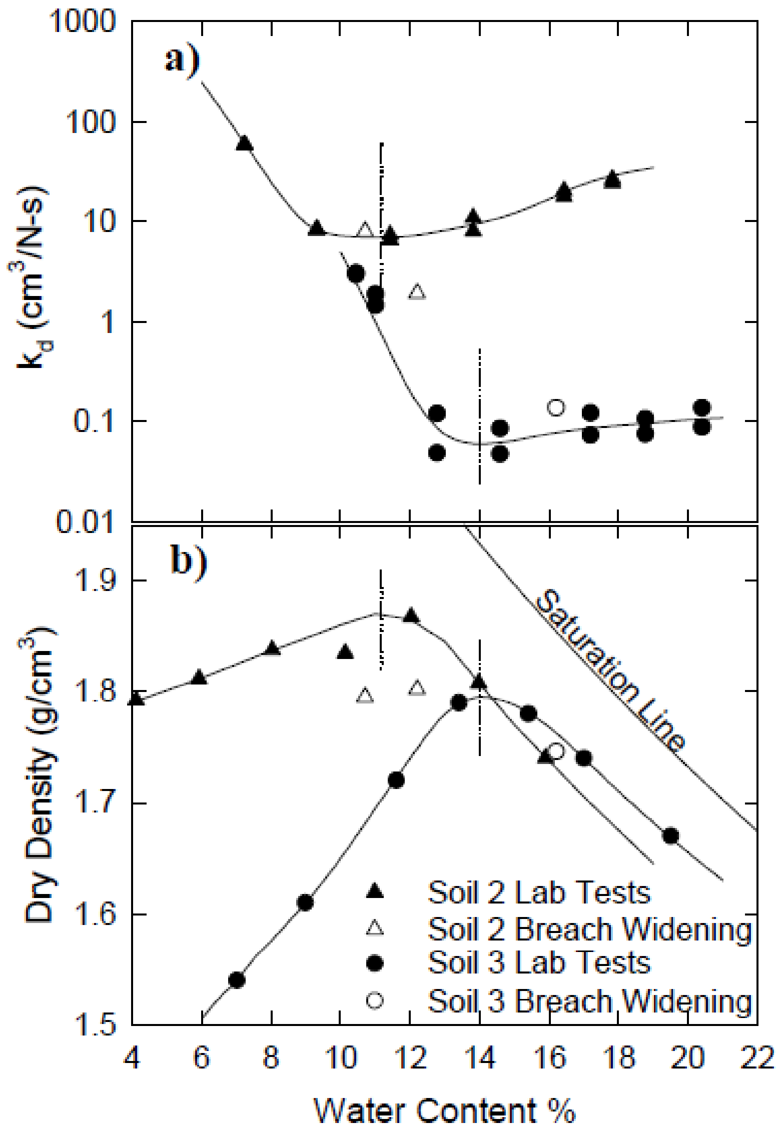


Figure 7. a) k_d vs. water content for Soil 2 and Soil 3, b) Dry density vs water content.

Compaction effort is also important

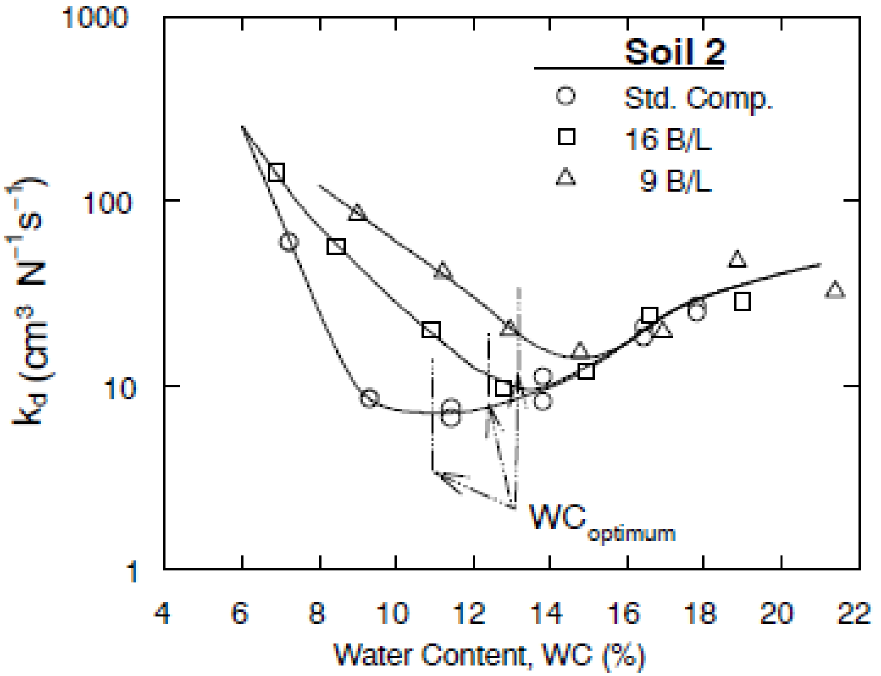


Figure 12. k_d vs. molding water content for standard, 16 B/L, and 9 B/L compaction effort of Soil 2.

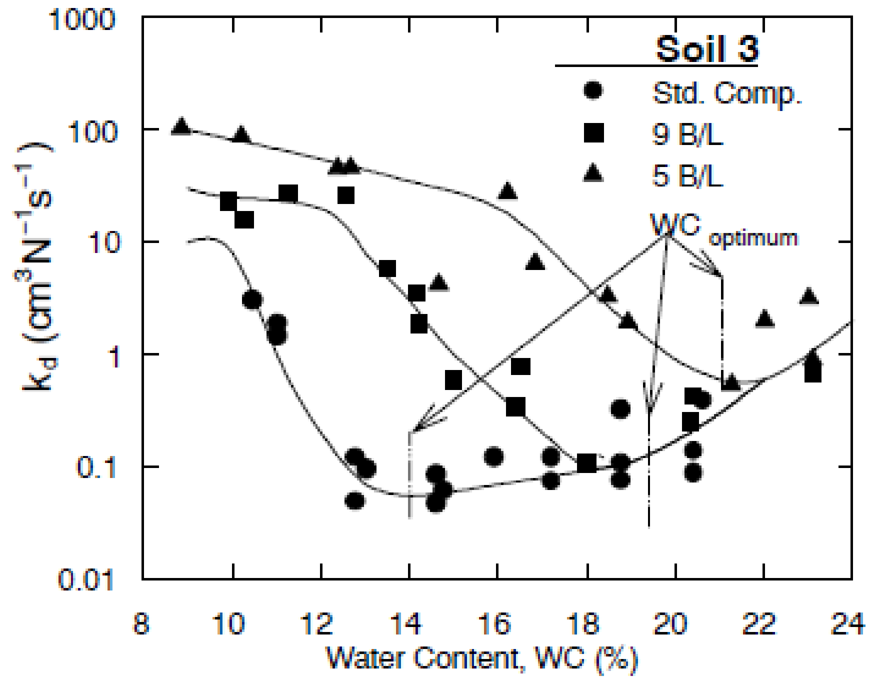


Figure 13. k_d vs. molding water content for standard, 9 B/L, and 5 B/L compaction effort of Soil 3.

Table 7. — Approximate values of k_d in $cm^3/(N\text{-}s)$ as a function of compaction conditions and % clay (Hanson et al. 2010). [1 $cm^3/(N\text{-}s)$ = 0.5655 ft/hr/psf]

% Clay (<0.002 mm)	Modified Compaction (56,250 ft-lb/ft³)		Standard Compaction (12,375 ft-lb/ft³)		Low Compaction (2,475 ft-lb/ft³)	
	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%
	Erodibility, k_d, $cm^3/(N\cdot s)$					
>25	0.05	0.5	0.1	1	0.2	2
14-25	0.5	5	1	10	2	20
8-13	5	50	10	100	20	200
0-7	50	200	100	400	200	800

Table 8. — Approximate values of τ_c in Pa as a function of compaction conditions and % clay (Hanson et al. 2010). [1 Pa = 0.0209 psf]

% Clay (<0.002 mm)	Modified Compaction (56,250 ft-lb/ft³)		Standard Compaction (12,375 ft-lb/ft³)		Low Compaction (2,475 ft-lb/ft³)	
	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%	≥Opt WC%	<Opt WC%
	Critical shear stress, τ_c, Pa					
>25	16	0.16	4	0	1	0
14-25	0.16	0	0	0	0	0
8-13	0	0	0	0	0	0
0-7	0	0	0	0	0	0

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Dam Breach Model Status Today

- WinDAM B
  - USDA-ARS (Stillwater, Oklahoma)
  - Homogeneous embankments
  - Vegetation or riprap slope protection
  - Overtopping only
  - Energy- and stress-based headcut erosion options
  - Public domain
  - Piping erosion module being developed…
  - Zoned embankments envisioned for future…

Dam Breach Model Status Today

- HR BREACH
  - HR Wallingford
  - Homogeneous or zoned embankments
  - Vegetation or riprap slope protection
  - Overtopping and piping
  - Energy-based headcut erosion
  - Surface erosion option (for granular materials)
  - <u>Monte Carlo simulation option</u>
  - NOT Public domain
    - Being used in consulting
    - Being incorporated into other tools (InfoWorks RS 2D, AREBA rapid appraisal tool for homogeneous embankment breach)

Simplified Methods

- When physically-based erosion and dam breach modeling is not justified or practical:
  - Breach parameters can be predicted using established regression equations
  - Does not help address the "will it fail?" question

- Can we put probabilities on ranges of breach parameters?

Probabilistic Breach Parameters

- No work has been done that specifically assigns probabilities
- Three studies in last 10 years have addressed uncertainty of breach parameters
  - Wahl (2004)
  - Froehlich (2008)
  - Xu & Zhang (2009)

Wahl (2004)

- Evaluated existing breach width and breach time equations to see how accurately they predicted observed values from case studies
- Uncertainties:

Breach width	± 1/3 order of magnitude
Breach time	± 1.0 order of magnitude
Peak outflow	± 0.5 to 1.0 order of magnitude

- USBR (1988), Von Thun & Gillette (1990) and Froehlich (1995) similar for breach width
- Froehlich (1995) peak flow and time equations were superior to competitors

Froehlich (2008)

- Revised breach parameter equations
  - Breach width
  - Time of failure
  - Side slope of trapezoidal breach opening
- Presented case study of using a Monte Carlo-type stochastic dam breach flood model
  - Inputs were breach parameters above, plus the critical overtopping head needed to trigger failure

Xu & Zhang (2009)

- Developed new equations using multi-parameter nonlinear regression techniques and different input variables
  - dam height, reservoir shape coefficient, dam type, failure mode, and dam erodibility (high, medium, low)
  - dam erodibility was most significant factor
- Performed uncertainty analysis to compare their equations to others

Breach Parameters in Risk Assessment

- Use uncertainty estimates and assumed probability distributions
- It is only practical to treat many parameters this way if you have a flood model that supports Monte Carlo simulation or equivalent

Xu & Zhang (2009)

- Failure time equations should be used with caution
- Approx. 30 dam failure cases were used to develop their failure time equations
- 9 dams used in their analysis were also used by Froehlich (1995)
  - Same failure time for 4 of the 9
  - Dramatically longer failure times for 5 of the 9 (4x longer)
  - No specific explanation of why they differ

Teton Dam

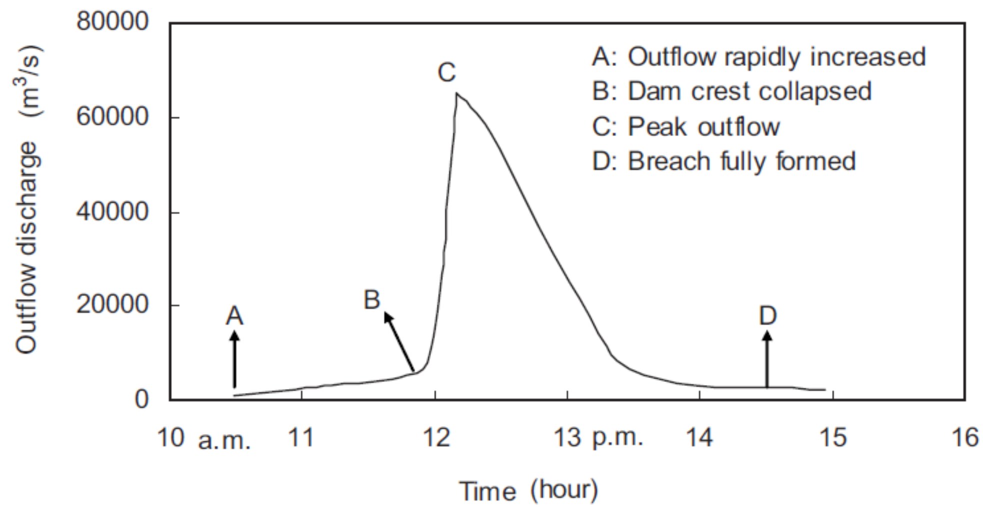

Fig. 3. Observed outflow discharge during failure of Teton Dam on June 5, 1976

- Froehlich T_f = 1.25 hr
- Xu & Zhang, T_f = 4 hr

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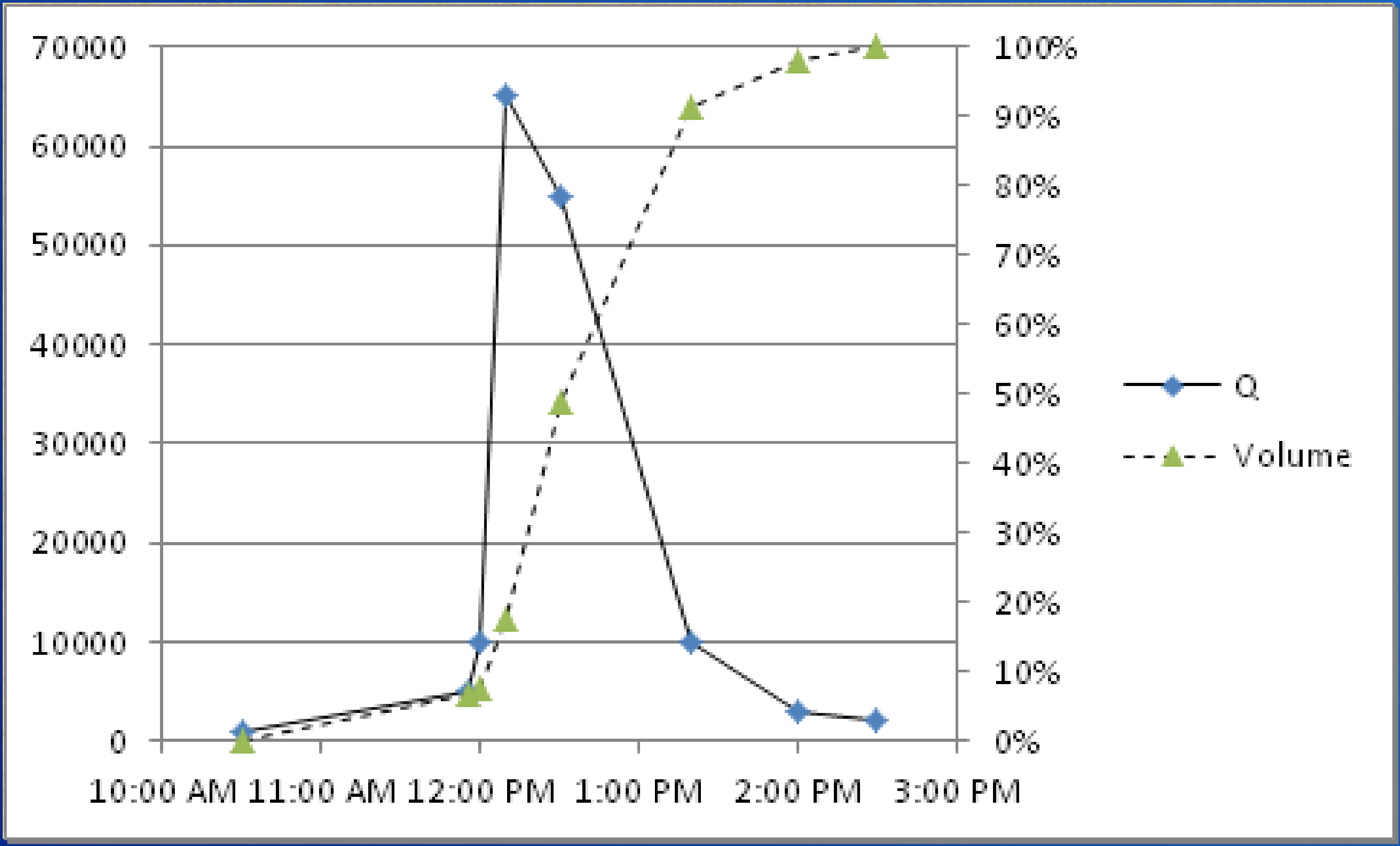
80% of volume released in 1.5 hrs



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Questions?

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