Issues
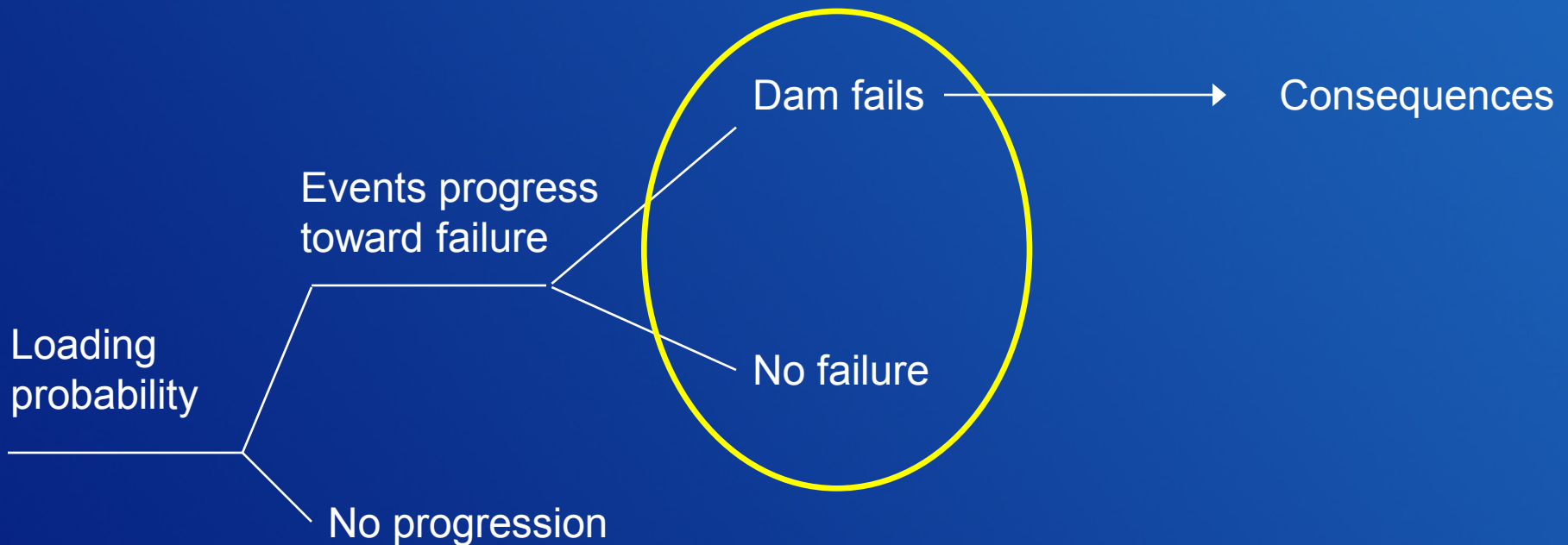
- **How to evaluate failure probability?**
- **How to estimate breach parameters in a probabilistic way?**
  - **Size of breach**
  - **Shape of breach**
  - **Time of failure (rate of erosion)**

- **Scope of this talk limited to embankment dams**

Failure Probability

- **Failure probability is a central question**

Loading
probability

Events progress
toward failure

No progression

Dam fails → Consequences

No failure

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…**

RECLAMATION

New Tools

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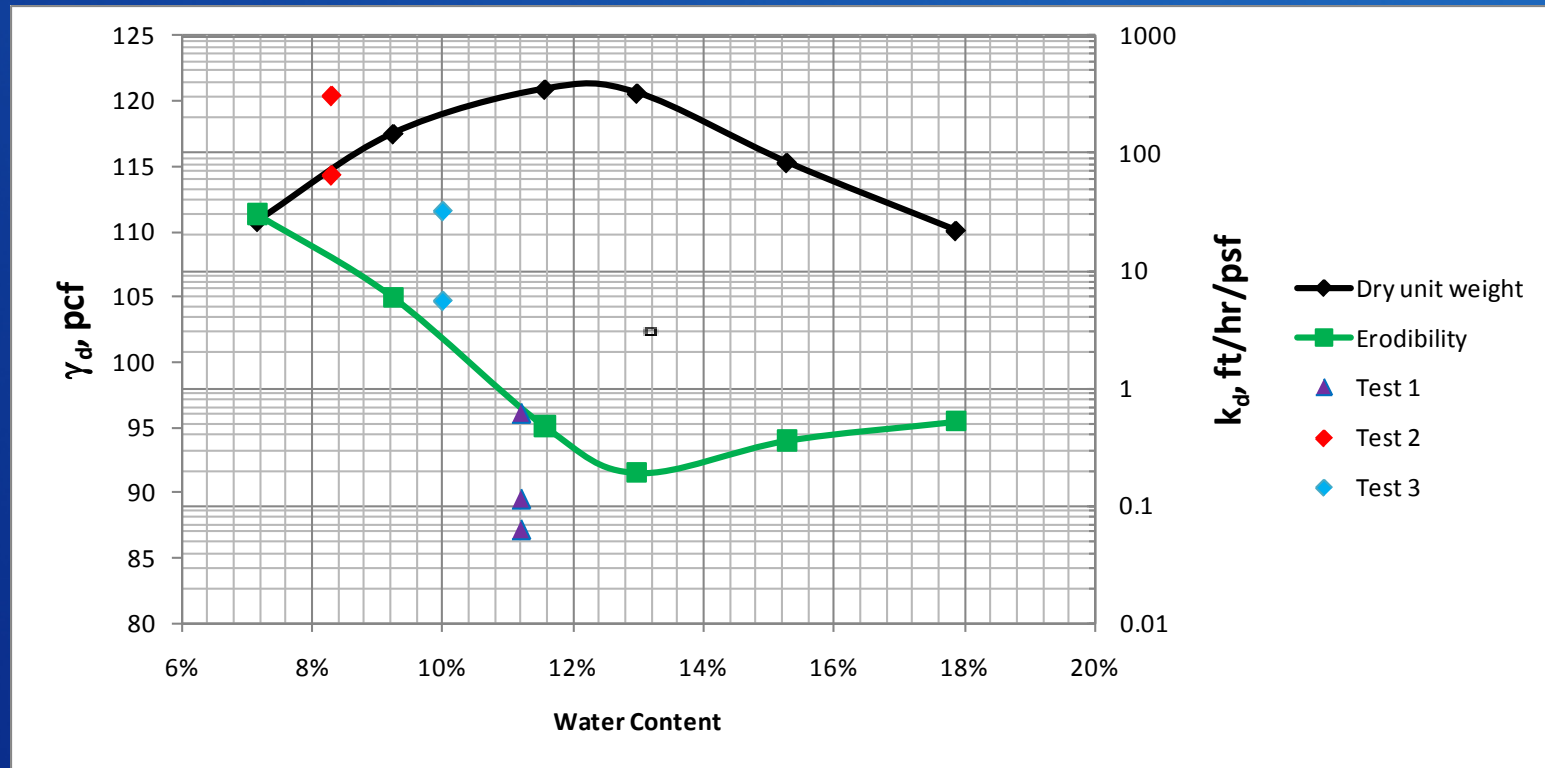
Dam Breach Models

- **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

$$\tau_i = \tau_o \left(\frac{J_p}{J_i}\right)^2 \text{ for } J_i \geq J_p$$
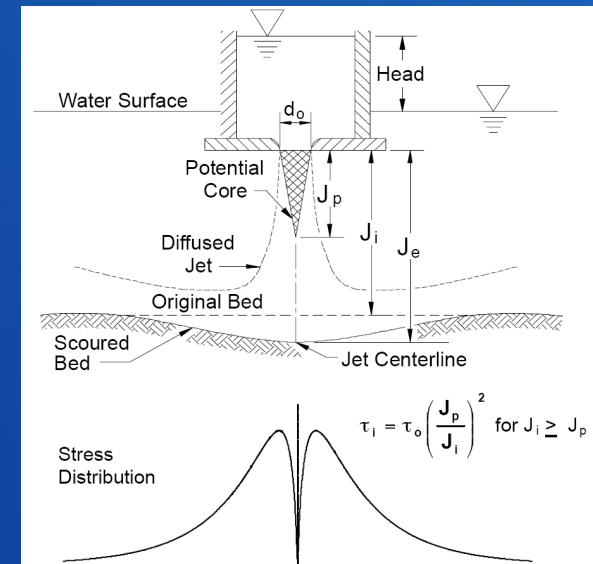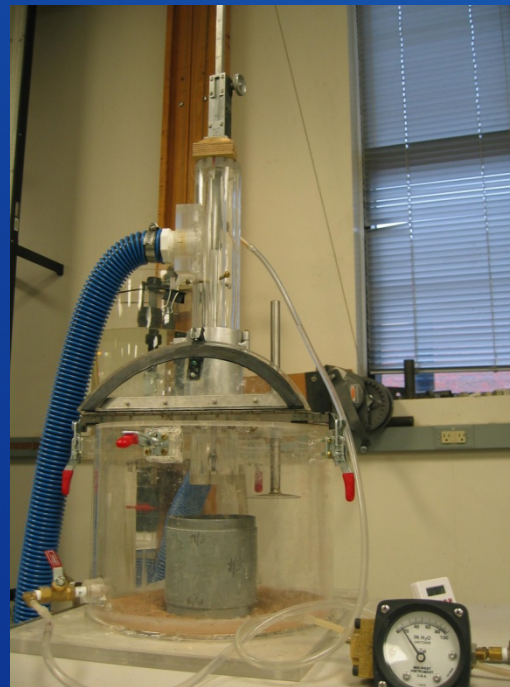
Compaction & Erodibility

RECLAMATION

Dam Breach Models

- **Output**
  - Determine <u>whether threshold for failure is reached</u>
  - Outflow hydrograph
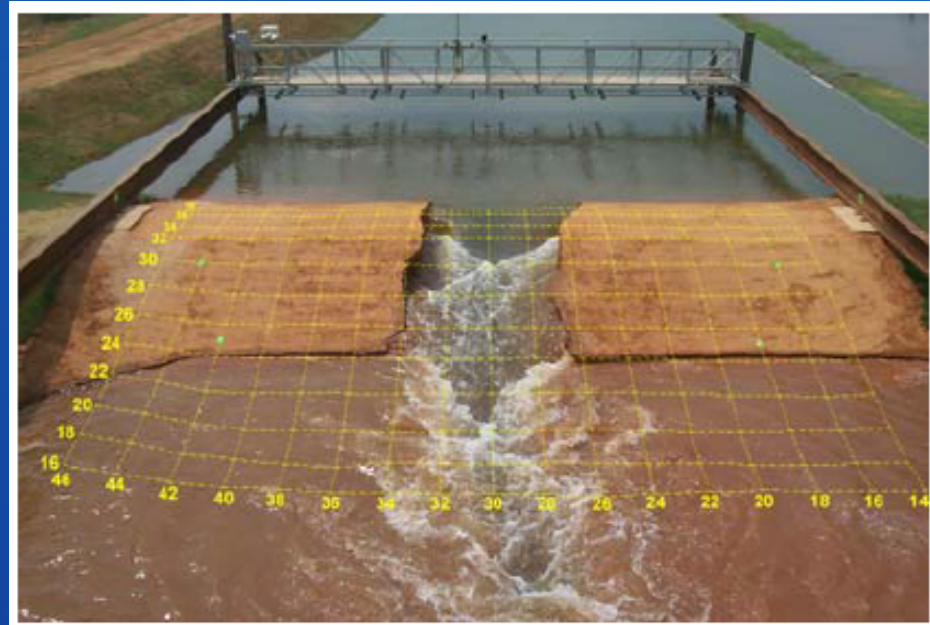 - Time-history of breach development

  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

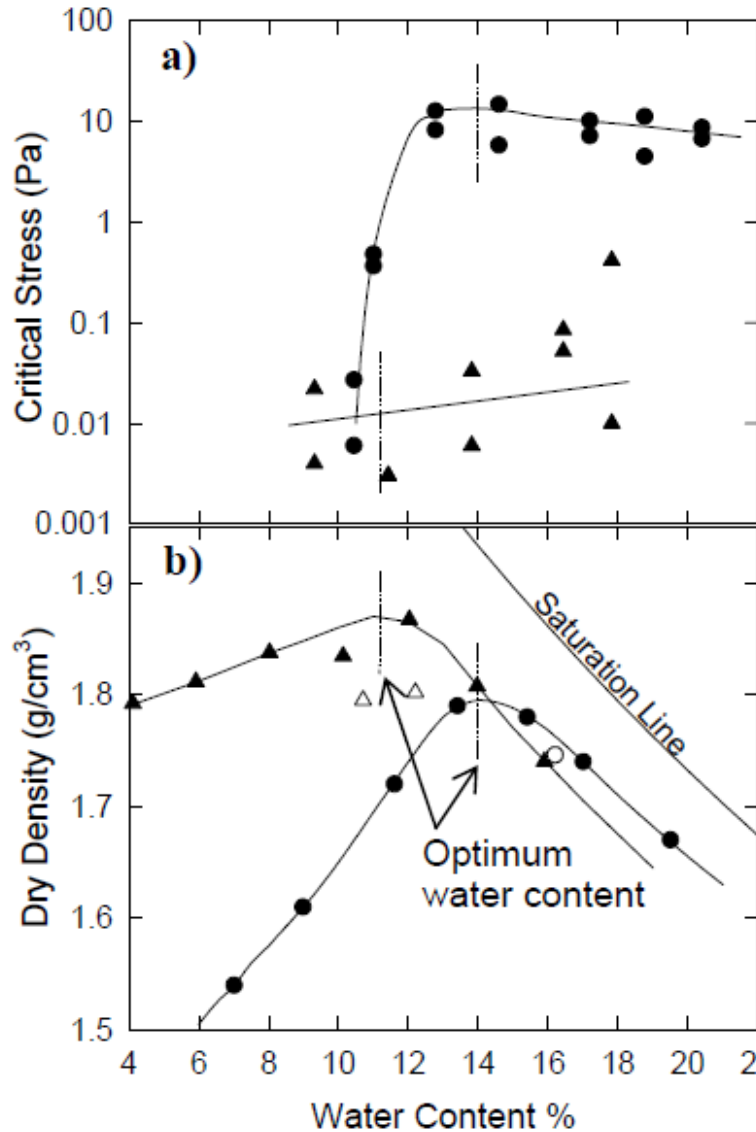RECLAMATION

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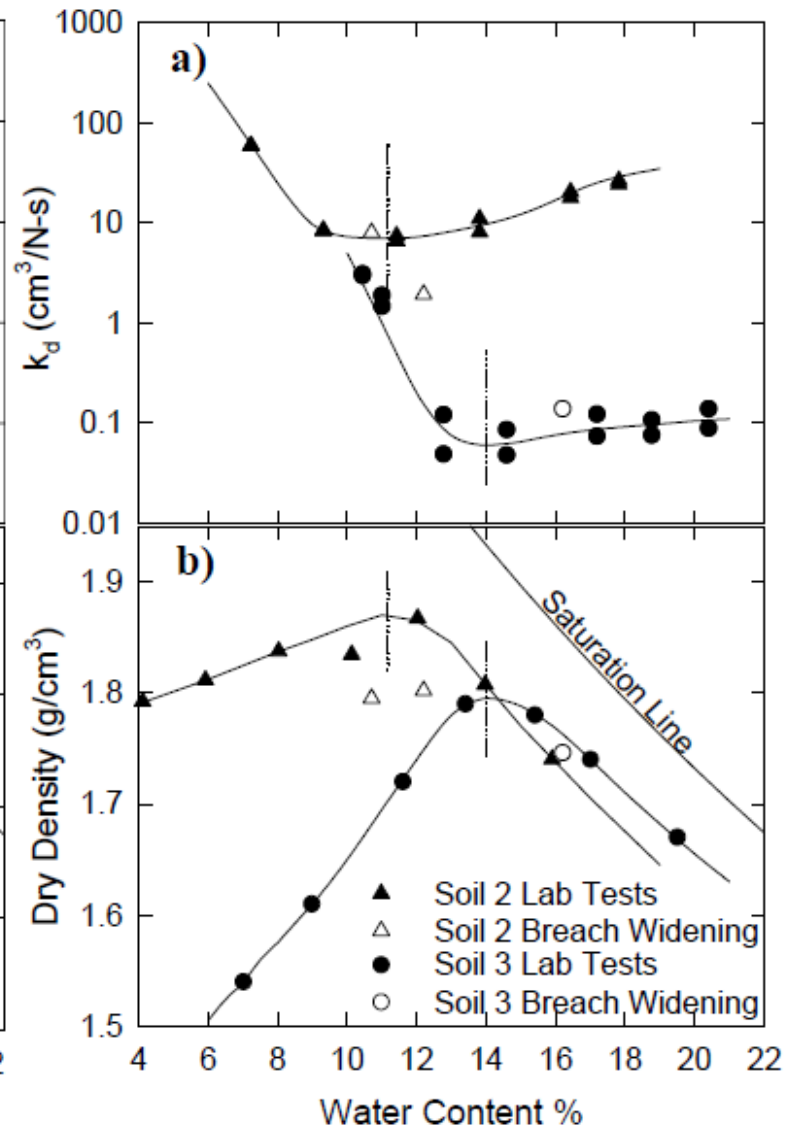
Figure 7. a) k_d vs. water content for Soil 2 and Soil 3, b) Dry density vs water content.

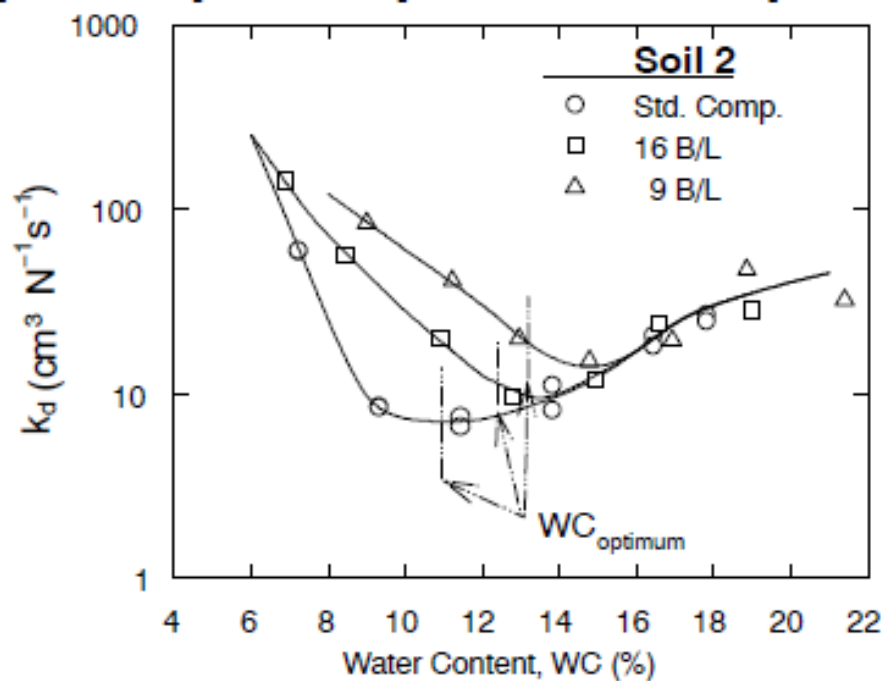Figure 12. k_d vs. molding water content for standard, 16 B/L, and 9 B/L compaction effort of Soil 2.
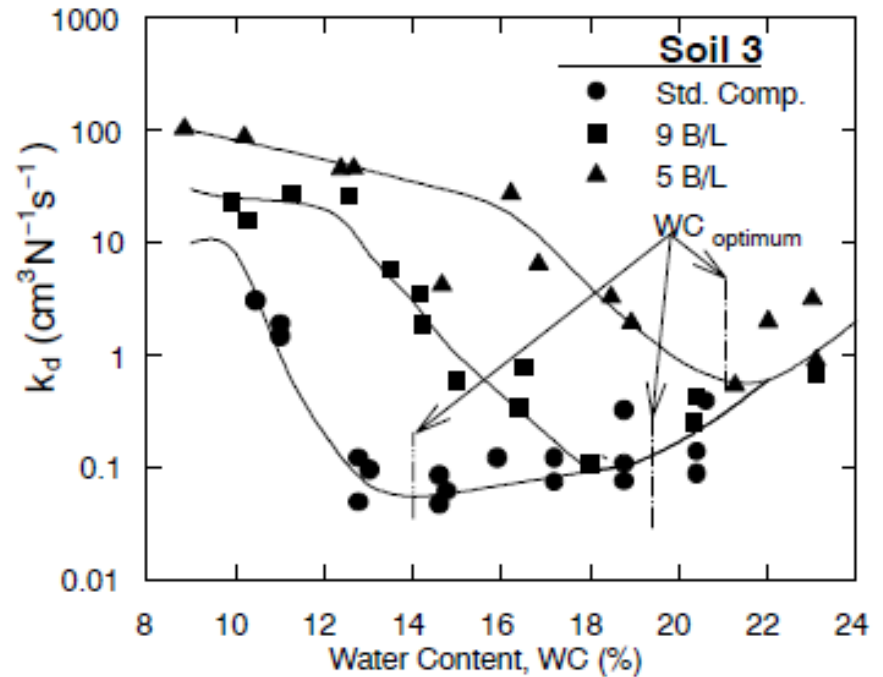
Compaction effort is also important

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

RECLAMATION

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…**

RECLAMATION

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)**
  - **Monte Carlo simulation option**
  - **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?**

RECLAMATION

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**

RECLAMATION

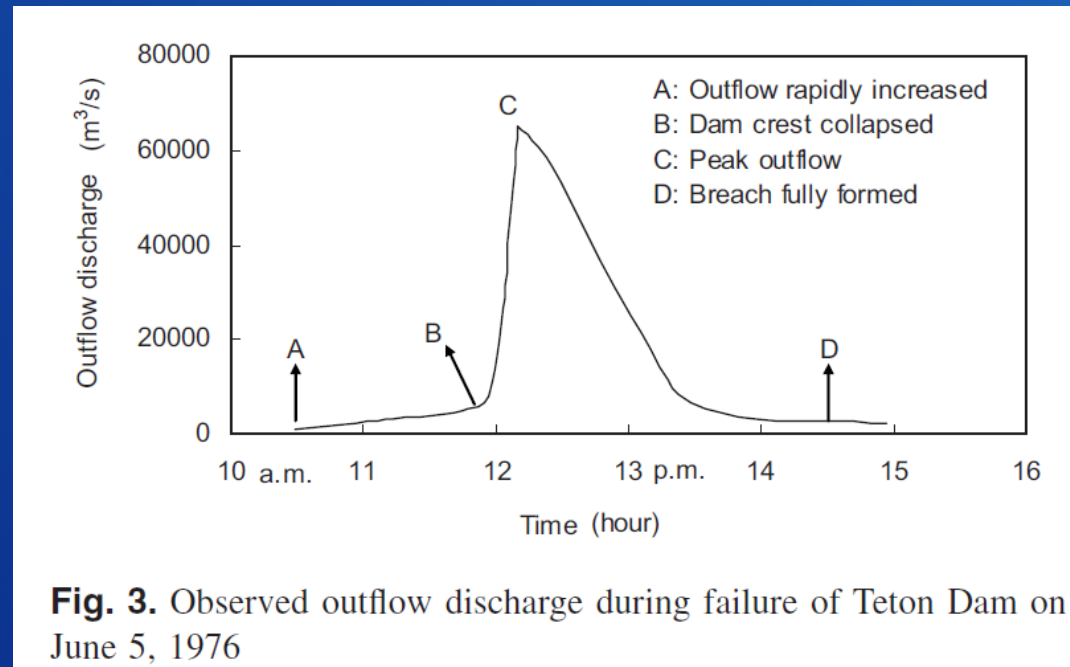# Breach Parameters in Risk Assessment

- **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**
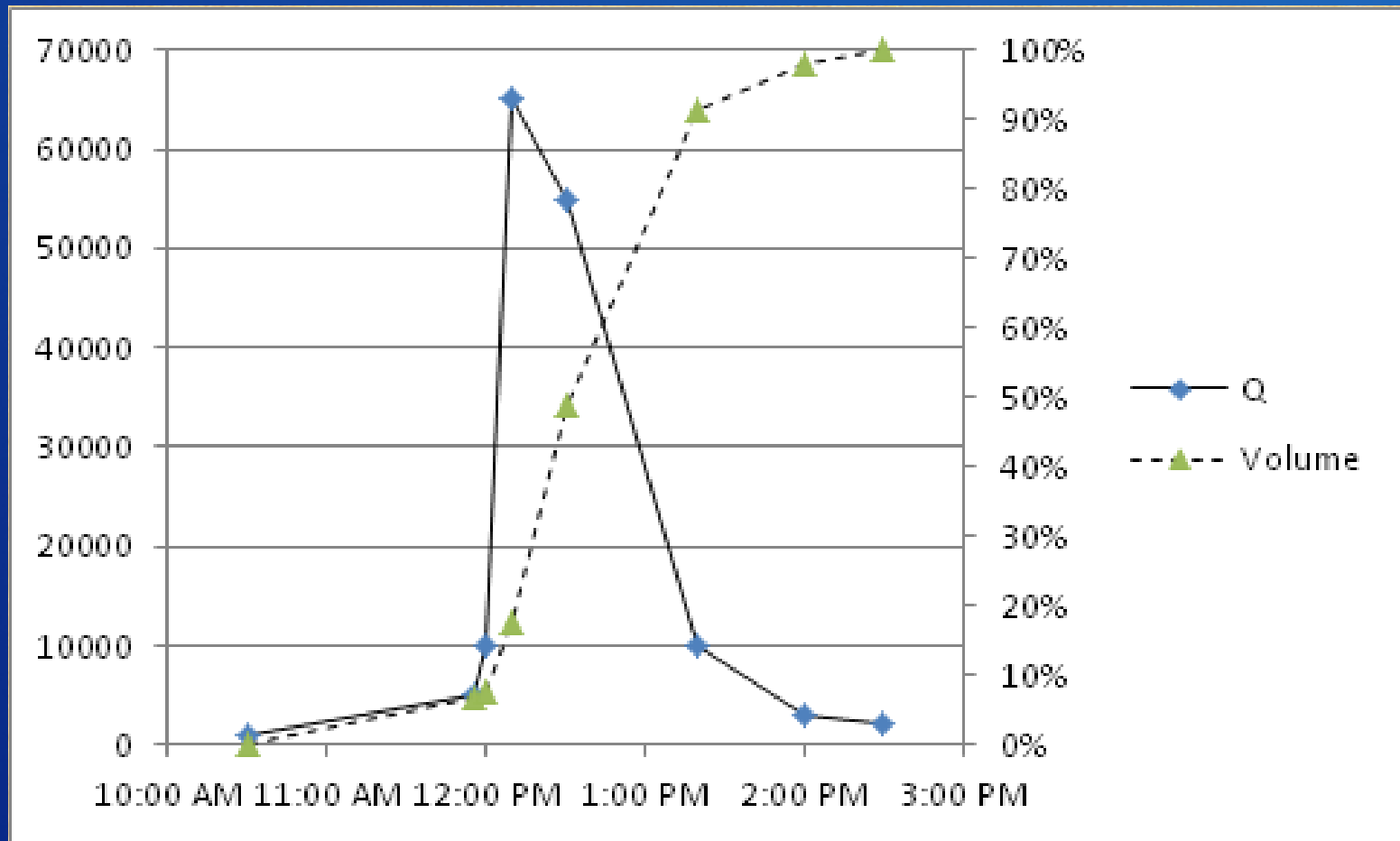
Xu & Zhang (2009)

- **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**

RECLAMATION

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**

80% of volume released in 1.5 hrs

Questions?