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Managing Water in the West

Modeling Overtopping Erosion Tests of Zoned Rockfill Embankments

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Overview

- Previously reported on three dam breach physical model tests performed for NRC by Reclamation's Hydraulics Lab
- Today: Focus on an overtopping flow test from that project
  - Discuss computational modeling of that test using two dam breach models
    - WinDAM C
    - DL Breach

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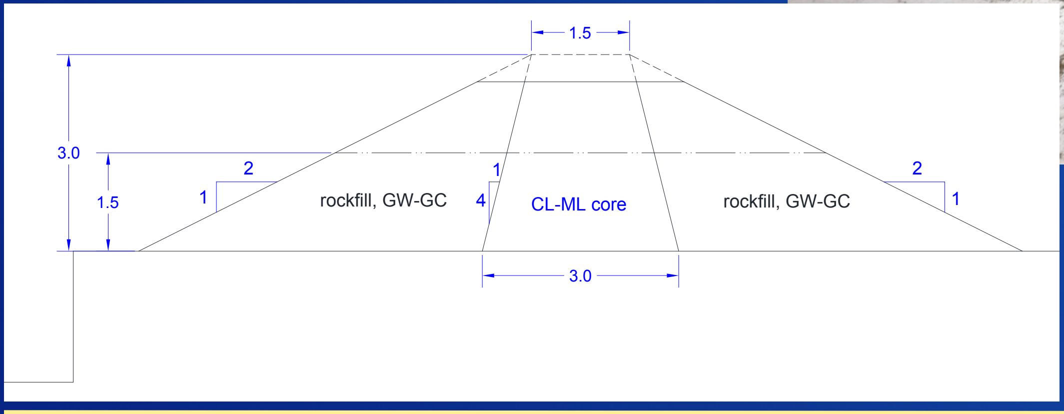
Dam Breach Test Facility

- 13-ft wide, 3-ft high embankment
- Silty clay core (CL-ML)
- Upstream and downstream "rockfill" zones (Well-graded gravel with clay) (a GW-GC roadbase soil)



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Embankment under construction

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Objectives

- Observe erosion and breach development mechanics
- Study relationships between applied stress, erosion resistance of embankment materials, and observed erosion rates

$$\varepsilon_r = k_d(\tau - \tau_c)$$

- Compare to numerical dam breach models

Overtopping Test – 3 minutes

Overtopping Test – 5 minutes

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Overtopping Test – 7 minutes

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Overtopping Test – 14 minutes

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Overtopping Test – 19 minutes

Overtopping Test – 26 minutes

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Overtopping Test – 33 minutes

Overtopping Test – 37 minutes

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Overtopping Test – 47 minutes

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Overtopping Test – 77 minutes

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Overtopping Test – 120 minutes

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Overtopping Test – 180 minutes

End of Test

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End of Test

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Material Behavior - cohesive

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Observations

- Despite cohesive behavior (near-vertical sidewalls), a headcut "step" did not develop. Dominant process was surface erosion of the breach channel invert.
  - Why no headcut?
    - Lack of tailwater pool to recirculate and erode toe
    - Erodible crest did not allow establishment of a free overfall

Examples of headcutting (USDA-ARS tests)

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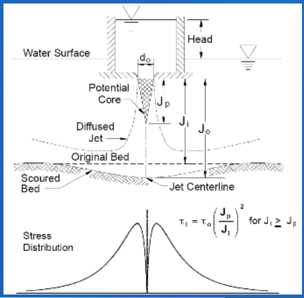
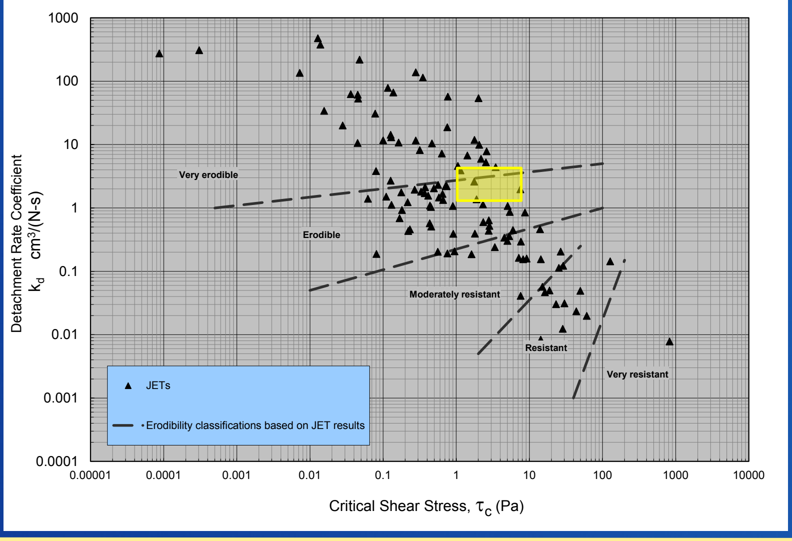
Post-Test Analysis



- **Estimated erosion rates and hydraulic stresses from photo records and used these to estimate values of k_d and τ_c**

$$\varepsilon_r = k_d(\tau - \tau_c)$$

- **Compared to JET tests**
- **Core and rockfill zones had similar erodibility $k_d \approx 0.7$ to 2.5 ft/hr/psf**



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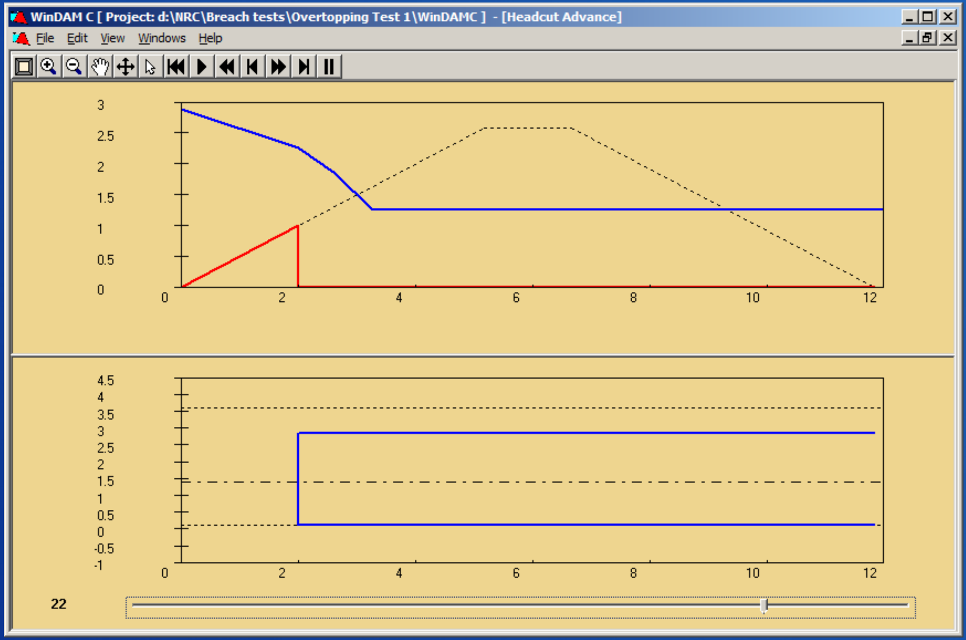
Applying Dam Breach Models

- WinDAM C – Model developed by USDA
  - Available since 2011
- DL Breach – Model developed by Dr. Weiming Wu (Clarkson University)
  - Available since about 2013
  - Algorithms being added to next HEC-RAS

WinDAM C (2011-2016)

- WinDAM C simulates overtopping and internal erosion failures of homogeneous, cohesive embankments
- For overtopping failures, breach development is by headcutting
- No surface erosion of crest



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WinDAM C Modeling Results

- For this application, because the crest does not erode down and there is a constant upstream reservoir level, the model predicts no increase in discharge until the headcut advances into the reservoir, then a rapid spike
- In contrast, in the lab experiment there was no headcut development or headcut advance. Instead, we observed significant surface erosion and lowering of the crest…with gradually increasing outflow

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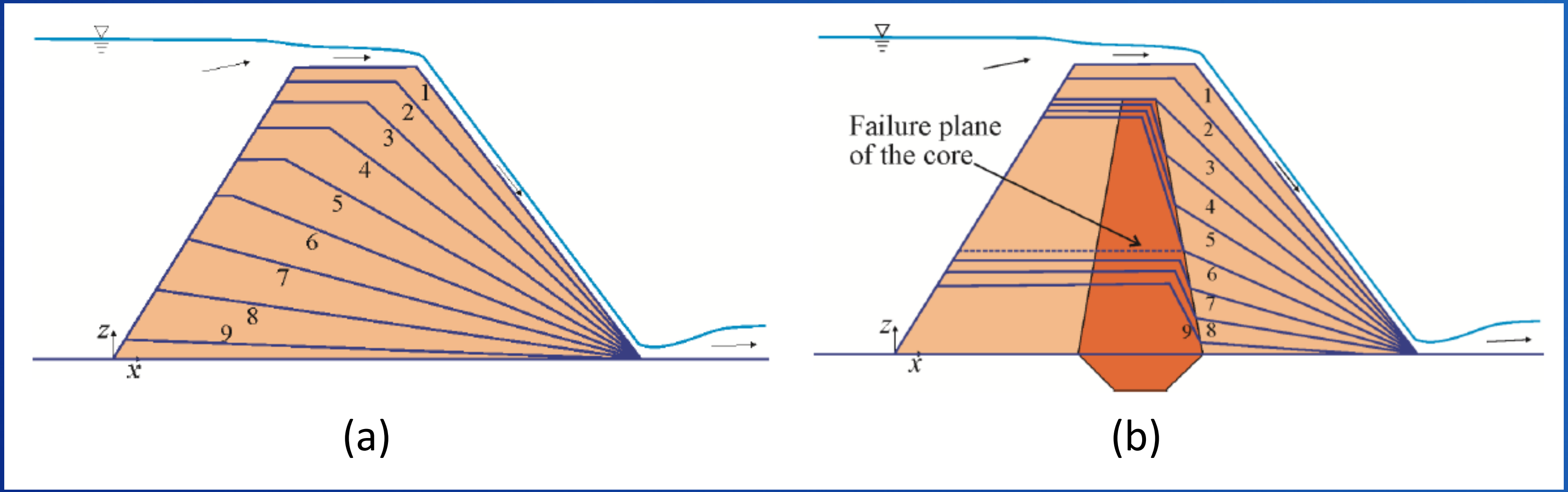
WinDAM C Modeling Results

- **WinDAM C did not accurately model our overtopping test**
- ***WinDAM C was developed for USDA dams, which tend to have enough initial erosion resistance of the crest (τ_c) that they consistently develop headcuts.***

DL Breach

- **DL Breach – dam and levee (DL) breach model**
  https://adweb.clarkson.edu/~wwu/DLBreach.html
- **Many options:**
  - Overtopping and internal erosion
  - Homogeneous and zoned embankments
  - Surface erosion, headcut erosion, and mass wasting mechanisms
  - Erosion models for cohesive and granular soils

DL Breach – Surface Erosion



- Erosion of crest surface and downstream slope are both possible
- With an erosion-resistant core this can give the appearance of headcutting, but mechanism is different
- May choose surface erosion models for either cohesive soil or granular soil (by zone)

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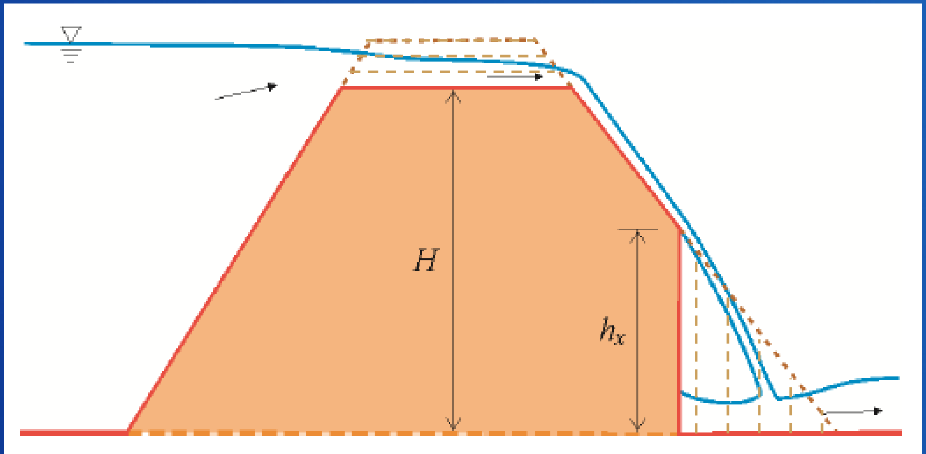
DL Breach – Headcut Erosion

- Can only be used for a homogeneous embankment
- Surface erosion of crest can also occur (cohesive or granular equations)
  - There is no surface erosion of downstream slope
- Three headcut model options:
  1. SITES model that uses headcut erodibility index K_h
  2. Temple (1992) model (the suggested option)
  3. Temple et al. (2005)
     - Similar to WinDAM C's energy-based model



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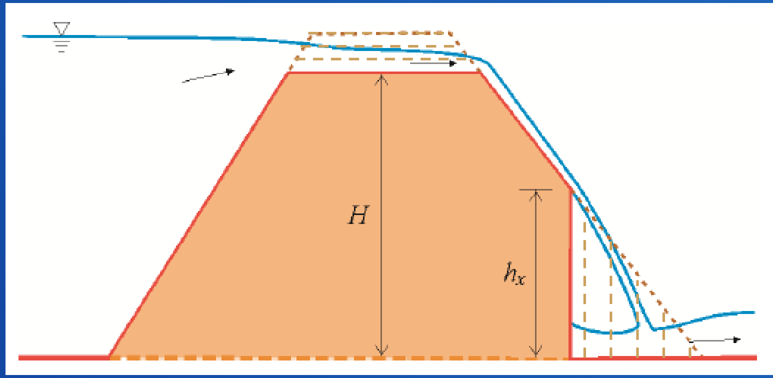
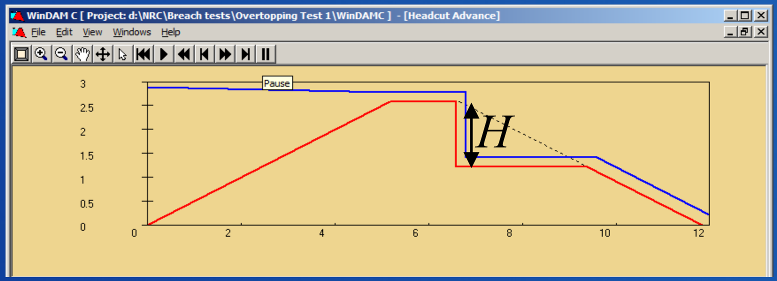
Headcut Models - Comparison

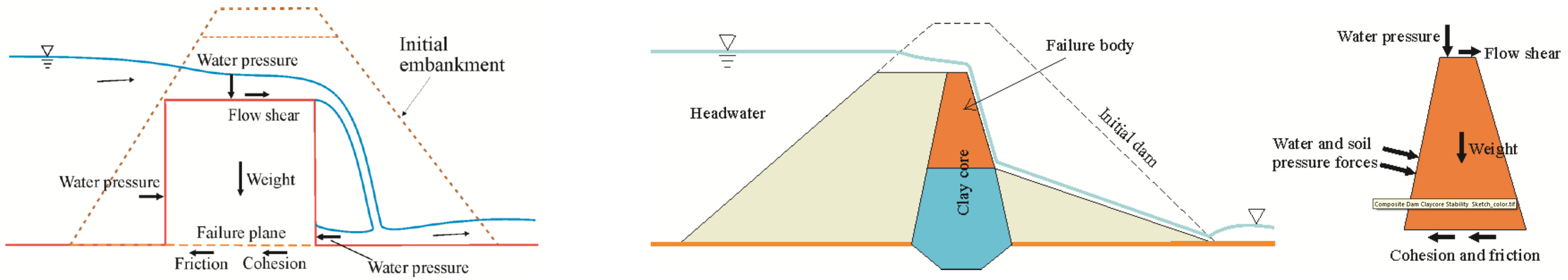
- **Although DL Breach option 3 and WinDAM C Energy-Based headcut appear outwardly “the same”, there are important differences.**
  - **Different initiation locations**
  - **Different head definitions (*H*)**
  - **Crest lowering**
  - **DL Breach uses multiplier (H/h_x) to accelerate initial headcut advance**





DL Breach Mass Wasting

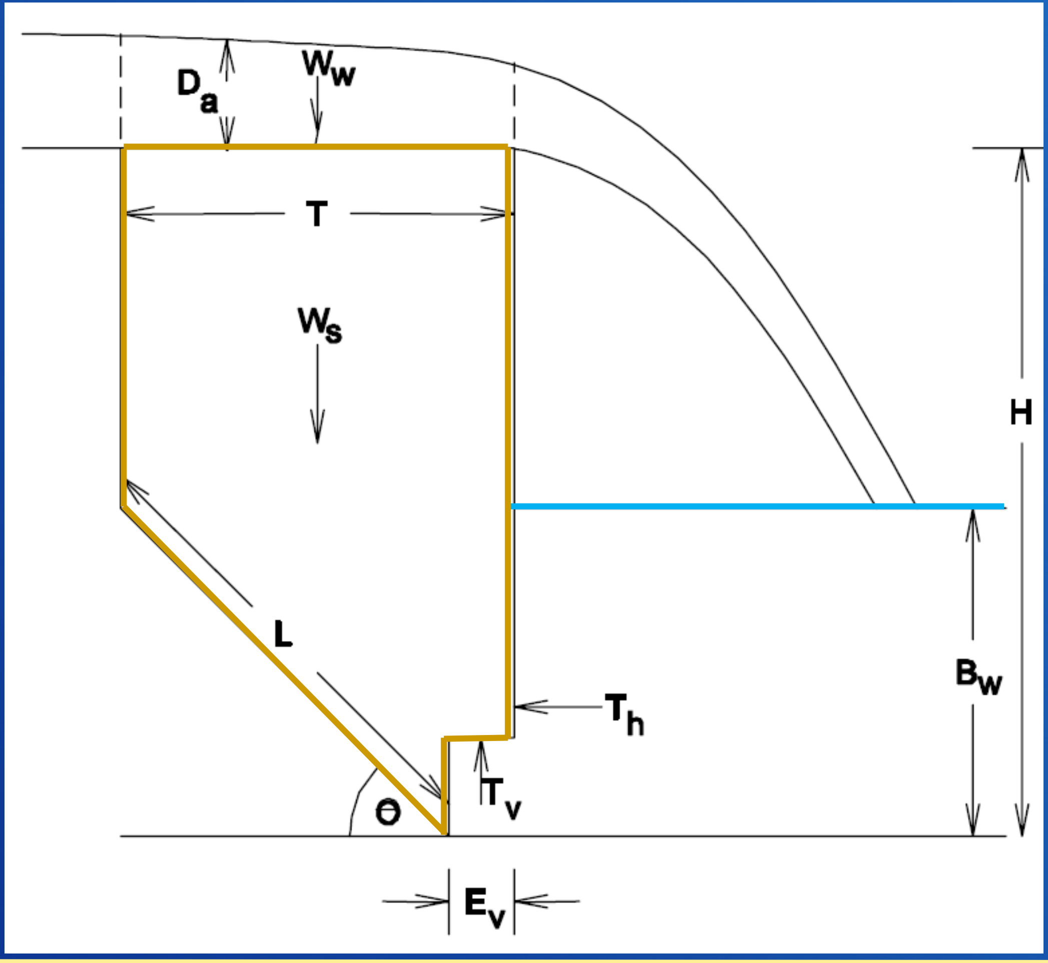
- In headcut mode (a), sliding failure of whole dam body is possible
- In surface erosion of zoned embankment (b), sliding failure through core is possible
- Slope failure of breach-channel sides is also possible – geotechnical force balance



(a) (b)

Mass Wasting – WinDAM C

- Headcut advance is a continuous mass wasting process at the headcut face, with rate of advance determined from force-balance
- No method for sliding of whole embankment or top section like DL Breach
- Breach channel widens in proportion to headcut advance rate



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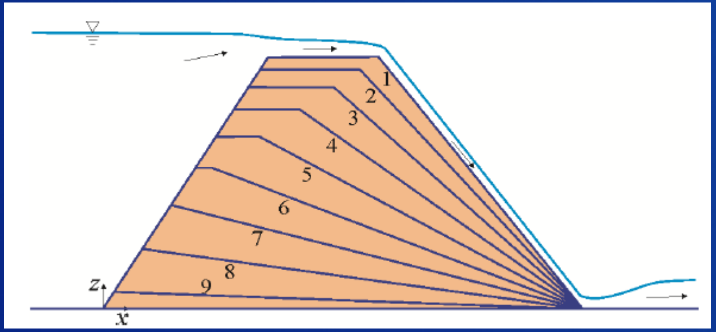
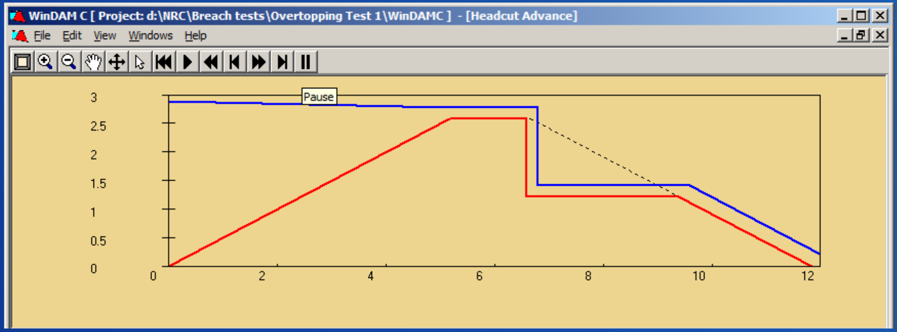
Erosion Equations Comparison

- DL Breach
  - Non-cohesive (granular) sediment transport equation
  - Cohesive sediment erosion by **excess stress equation**



- WinDAM C
  - **Excess stress equation** for initial erosion of downstream slope and deepening of headcuts



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DL Breach – Granular Sediment

- Total transport capacity is the sum of suspended load (Zhang 1961) and bed-load (Wu et al. 2000) capacities
- Bed load transport rate is a function of "grain shear stress"

$$\tau_b' = \left(\frac{n'}{n}\right)^{3/2} \tau_b$$

τ_b is total bed shear stress

n' is Manning's n of sediment grains, n is Manning's n of whole channel

- The ratio $(n'/n)^{3/2}$ "partitions" the stress into the part that actively causes transport of soil grains vs. the part that acts upon bed forms

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DL Breach – Cohesive Sediment

- **Does not partition the stress…total bed stress is used to calculate detachment rates using the linear excess stress equation**

$$\varepsilon_r = k_d(\tau_b - \tau_c)$$

- **In contrast, WinDAM C uses "erosionally effective stress" to develop and deepen headcuts**

$$\tau_b' = \left(\frac{n'}{n}\right)^2 \tau_b$$

$$\varepsilon_r = k_d(\tau_b' - \tau_c)$$

Applying DL Breach to the NRC zoned embankment overtopping test

- Zoned embankment with surface erosion, using cohesive soil erosion equations for all zones
  - Seemed like good match to observed soil behavior
- Zoned embankment with surface erosion, using granular sediment transport equations
  - Because this might be more appropriate for gravel zones
- Homogeneous embankment with headcut
  - (Not relevant since no headcutting was observed)
- Homogeneous embankment with surface erosion
  - (Cohesive equations)

A real challenge is no graphical output, only time series of breach bottom elevation and width, upstream and downstream slope, and breach outflow…hard to visualize what is happening

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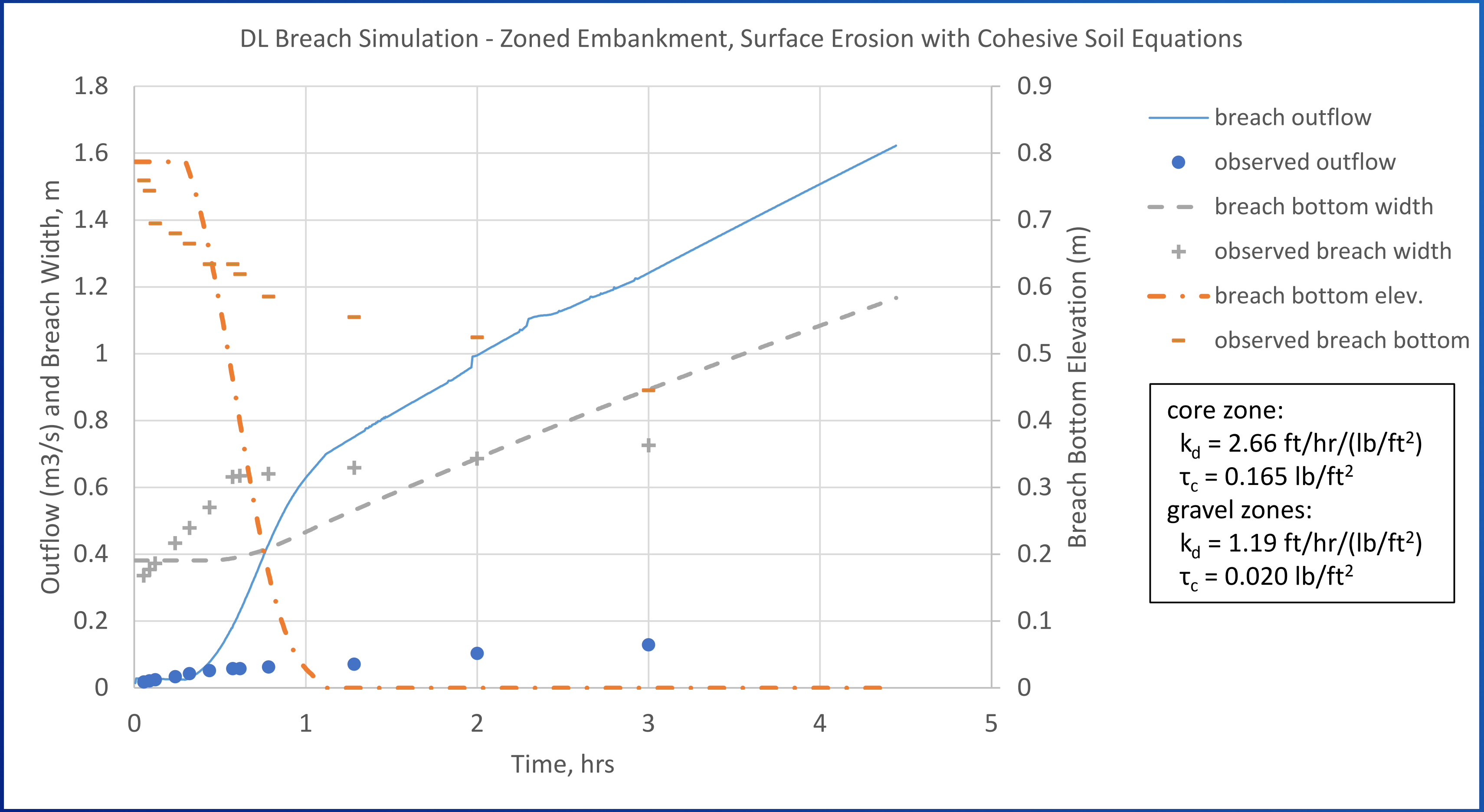
Results

- Zoned embankment with surface erosion, using cohesive soil erosion equations
  - Initial runs made using erodibility parameters estimated from test results did not match well
  - Problem was that test results were analyzed with effective stress methods (WinDAM approach), but DL Breach uses total stress
  - Significant reduction of erodibility coefficients (k_d) was needed

Poor Result – breach forms too quickly and grows too large, too fast



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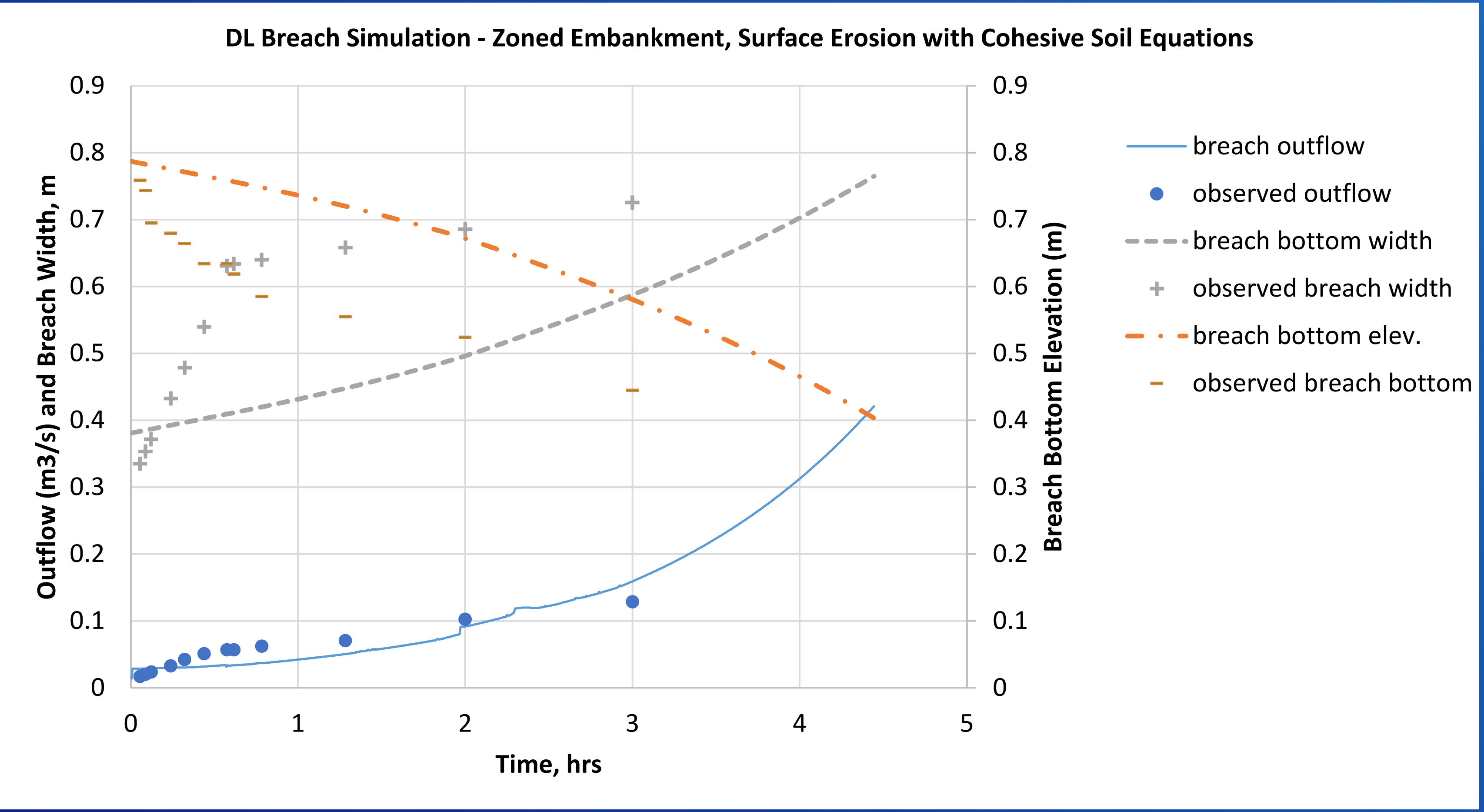
Better Result



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Results

- Zoned embankment with surface erosion, using granular sediment transport equations
  - No suitable combination of inputs could be found that produced a realistic result
  - A large mass-wasting event seemed to be occurring in some runs (big change in outflow), but was difficult to interpret from limited output

Results

- Homogeneous embankment, surface erosion
  - Similar result as zoned embankment with surface erosion of cohesive soils
  - In this experiment the different zones had similar erodibility (even though much different soil types), so zoned vs. homogeneous did not make much difference.

Model Comparison Summary

- Some obvious differences, plus some significant differences even in parts that seem outwardly similar
- Crucial for modeler to know algorithm details and how erosion mechanisms interact
- Ability to “see” intermediate stages of breach development is important for knowing what the models are doing
  - This is difficult in DL Breach…better in WinDAM C
    - HEC-RAS implementation may improve this