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Managing Water in the West

Evaluation of Dam Breach Models

CEATI Dam Safety Interest Group (DSIG)

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Outline

- Overview of Erosion and Breaching of Embankment Dams project
- Computational Dam Breach Model Evaluation
  - Models
  - Case studies
  - Findings
- Subsequent Developments

CEATI International

Centre for Energy Advancement through Technological Innovation (CEATI)

- **A consortium of 130+ energy-industry organizations collaborating on research and technology development through 18 interdisciplinary focus groups**
  - **Dam Safety Interest Group**
  - **Evolved from the Canadian Electricity Association (1891) and is now international in scope**

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Project Description

- DSIG Working Group on Erosion and Breaching of Embankment Dams organized in 2004
- Objective to improve physically-based computer models for simulating embankment dam erosion and breach

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Participants

- Electricité de France
  - Case studies…erodimeter and piping erosion research
- Hydro Québec / Ecolé Polytechnique Montréal
  - Numerical modeling of dam breach, development of Firebird breach model
- Bureau of Reclamation
  - Laboratory testing…investigate methods for measuring erodibility
- Agricultural Research Service
  - Large-scale laboratory testing and development of SIMBA/WinDAM models
- HR Wallingford
  - Large-scale testing (IMPACT project), developers of HR-BREACH model
- US Army Corps of Engineers
  - Model evaluation, owners/developers of HEC-RAS suite
- Elforsk
  - Model evaluation

- Sponsors and other interested parties
  - BC Hydro, Churchill Falls, EoN Vasserkraft, Great Lakes Power, Manitoba Hydro, New York Power Authority, Ontario Power Generation, Seattle City Light, Scottish & Southern Energy, National Weather Service

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Approach

- **2004-2006 Phase I**
  - **Gathered lab and case study dam failure data**
  - **Identified leading models under development**
- **2007-2009 Phase II**
  - **Compared JET and HET methods for measuring soil erodibility (key input to newer breach models)**
  - **Evaluated physically-based breach models by running and comparing against lab and case study data**

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Computational Model Evaluation

- **Three models initially identified**
  - **SIMBA (USDA-ARS)**
  - **HR BREACH (HR Wallingford)**
  - **Firebird (Montréal Polytechnic)**
- **Seven case studies chosen for modeling**
  - **2 ARS dam breach tests (*Oklahoma*)**
  - **3 tests from IMPACT Project (*Norway*)**
  - **2 real dam failures (Oros: *Brazil*, Banqiao: *China*)**

SIMBA / WinDAM family of models

- Developed by USDA-ARS (Stillwater, Oklahoma)
- SIMBA was the research and development vehicle
- WinDAM is the end product for public use
  - WinDAM A/A+, 2008, allowable overtopping (no breach)
  - WinDAM B, 2011
    - Homogeneous embankments
    - Overtopping flow only
  - WinDAM C, 2016
    - Internal erosion

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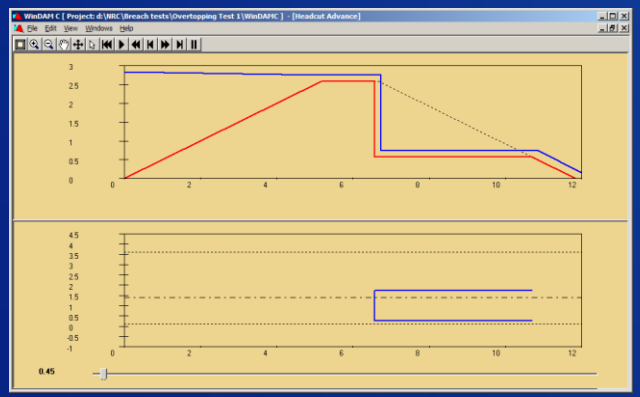
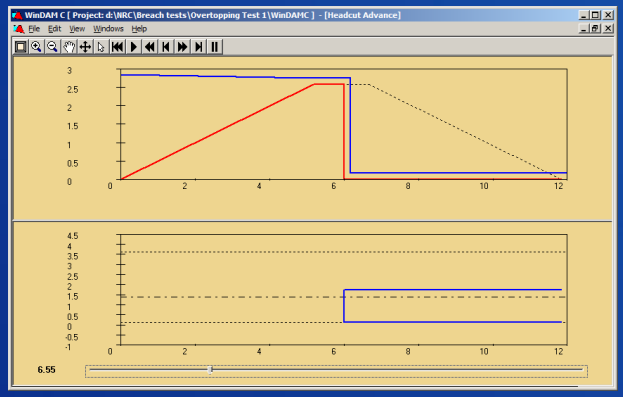
SIMBA compared to WinDAM

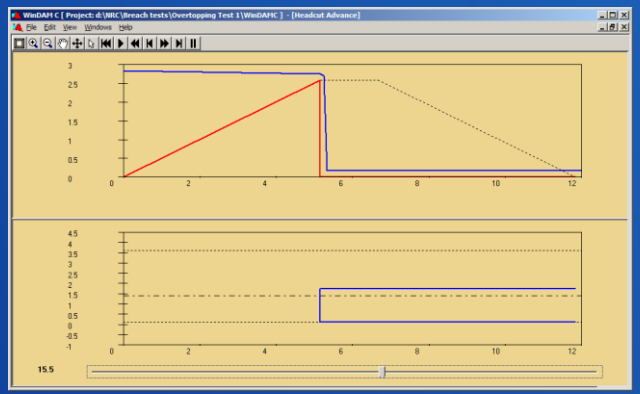
- SIMBA was configured to analyze lab tests
  - Pilot channel
  - Bare earth (no vegetation or riprap armoring)
  - Switchable modules for different erosion algorithms
    - Version we evaluated used only a deterministic (stress-based) headcut erosion model
    - Final release of WinDAM also includes an empirical energy-based model

SIMBA Erosion Mechanism

- Headcut erosion (developed for cohesive embankments, matching USDA inventory)
- Headcuts deepen and advance upstream, no crest lowering
- Breach outflow does not increase significantly until headcut enters reservoir







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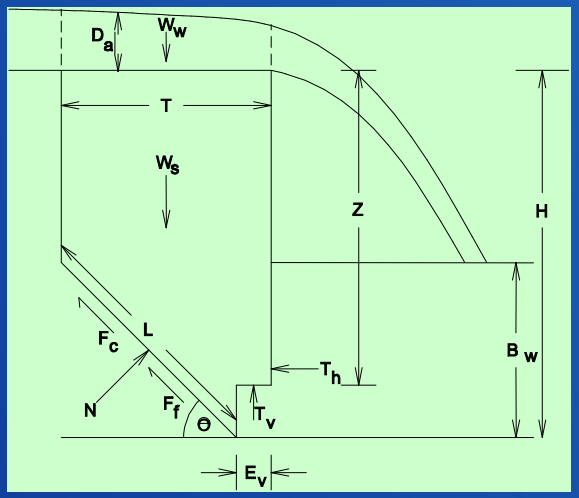
SIMBA Erosion Equation

- Linear excess stress equation used for all key erosion processes
- Downstream slope of dam (to initiate, develop, and deepen headcuts)
- Toe of headcut face
  - applied stress
  - erosion resistance
  - observed erosion

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



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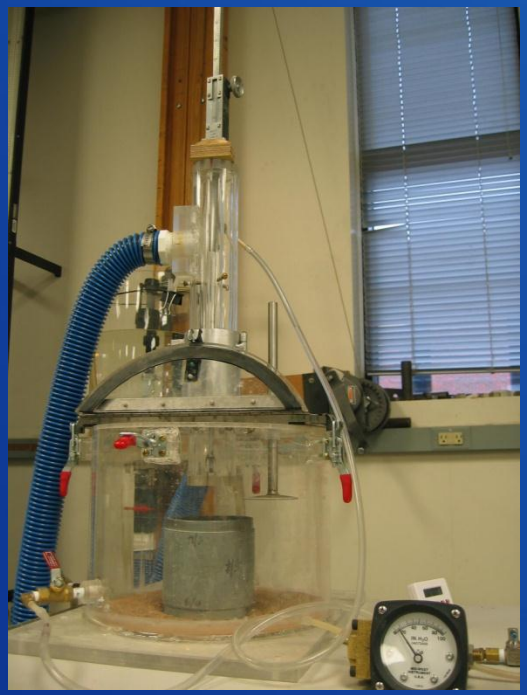
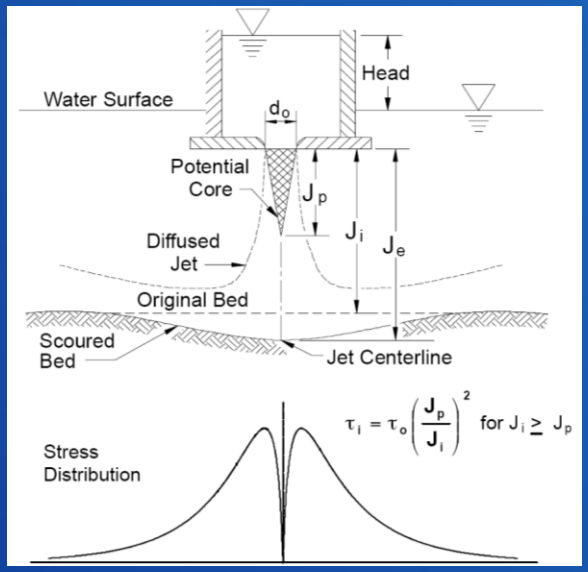
Submerged Jet Test: k_d and τ_c





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HR BREACH

- **Developed at HR Wallingford**
  - **Homogeneous or simple zoned embankments**
  - **Overtopping or piping failure modes**
  - **Piping and zoned embankment features were not extensively developed at time of the evaluation**
- **Subsequent development has produced the EMBREA model**
  - **Greatly improved zoned embankment flexibility**

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HR BREACH compared to SIMBA

- **Options for surface erosion with multiple erosion equation options (including excess stress equation), or headcut (same energy based model as in WinDAM B/C…no stress-based headcut)**
  - **Relied upon surface erosion option for the DSIG model evaluation to intentionally compare the different modeling approaches**

The Case Studies

- Two USDA overtopping tests (Oklahoma), 1.75 m
  - One embankment breached, silty sand
  - One embankment damaged, but not breached, headcut advanced partially through, lean clay
- Three IMPACT tests (Norway), 5-6 m
  - Cohesive dam (clayey silt)
  - Gravel dam, well graded
  - Composite (zoned) dam, different gravels in each
- Oros Dam, zoned, thick clay core (weak), 36 m
- Banqiao Dam, homogeneous, weak clay, 25 m

Quality of Case Studies

- **USDA tests – VERY GOOD**
  - **Good knowledge of materials, compaction, in situ JET tests to measure k_d, τ_c**
  - **Good control and measurement of inflow, outflow, reservoir levels**
- **IMPACT – FAIR**
  - **Some key material properties not well known**
  - **Limited measurements of erodibility, gravel materials beyond ability to directly measure k_d**
  - **Poor control of inflow & reservoir conditions in some tests**
- **Oros, Banqiao – POOR**
  - **Very limited materials information**
  - **Many uncertainties about inflow, outflow, reservoir levels**

Evaluation Approach

- **Modelers provided two results for each application of each model to each case study**
  - **Initial run based on available data and group discussion of how to best interpret limited information**
  - **Improved run in which adjustment of inputs and modeling options was allowed within reason**

Results - General

- Breach outflows and breach widths were modeled with reasonable accuracy by both models, with significant adjustments required for some cases
- Breach widening rates, breach initiation times, and breach formation times were more difficult to model accurately
- Getting timing of breach initiation matched to inflow boundary conditions is crucial
  - Reservoir water level boundary specification is needed

Results – Model Strengths

- SIMBA performed well on the cohesive embankments, as expected
  - HR BREACH required use of headcut mode to get good agreement in some cases
- HR BREACH had better flexibility to model the IMPACT gravel dams due to surface erosion capability and erosion models
  - These required careful adjustment due to the uncertain boundary conditions

Results – Real Dam Failures

- Oros and Banqiao cases were very difficult to model because of multiple uncertainties
  - Inflow hydrographs, reservoir levels
  - Actual breach outflow hydrographs
  - Material properties almost unknown
  - Tailwater appeared to be important at Oros
    - SIMBA had limited ability to model tailwater influence (research model)
    - WinDAM addresses this

Subjective Comparison

Evaluation Summary	HR-BREACH	SIMBA/WinDAM
Erosion Process Models	Good	Good
Surface protection	Vegetation and rip-rap using CIRIA curves	Vegetation and rip-rap in WinDAMb
Headcut erosion processes	Good; energy-based only	Best; both stress-based and energy-based
Surface erosion processes	Yes	No
Mass-wasting / soil-wasting processes (bank failures, arch collapse)	Stress-based bank failures and arch failure	Bank failures implicit
Piping progression	Yes	In development
Intangibles		
Data Input Guidance	Good	Good
Ease of Use	Good	Best
Computational Efficiency	Good	Best
Documentation	Excellent	Excellent
Organizational Support for Continued Development	Good	Good
Embankment Geometry Options	Simple Zoning	Homogeneous

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Key Conclusions

- **SIMBA/WinDAM and HR-BREACH models were both very capable**
  - **Similar in many respects**
  - **A few differences that gave each an advantage in specific cases**
  - **Both models are being supported by organizations working to sustain their development**
- **Modeling expertise of users is crucial**
  - **Many options and complex interactions of erosion processes and boundary conditions**
  - **User understanding of soil erodibility and availability of good information is crucial**

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Research Needs

- Erodibility parameters for coarse-grained soils and mixtures of coarse- and fine-grained soils are needed
- Criteria are needed to determine when headcut erosion or surface erosion will develop
  - Material behavior is a major influence
  - Tailwater conditions may also be important