Estimating Dam Breach Parameters

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Outline

• Defining a breach parametrically
• How are breach parameters used?
• Regression equations for predicting breach parameters
  – Review commonly used equations
  – Highlight recent developments
• Review how breach is modeled in tools to be discussed in the seminar
Why Breach Parameters?

• Many models for predicting breach outflow simulate hydraulic processes, but use breach parameters to simplify modeling of breach development processes
  – Concrete dams (arch, gravity, buttress, etc.) **
  – Embankment dams (homogeneous, zoned, filter zones, core walls, concrete facing, non-cohesive, cohesive)
  – Erosion processes: sediment transport, headcutting, slope failures, side-slope failures, mass sliding, etc.
Defining a Breach Parametrically

- To **model breach outflow**, we must...
- Describe breach geometry vs. time
  - Boundary condition that regulates breach outflow
- Breach parameters
  - shape and maximum size
  - time for development
  - functional representation vs. time
    (linear, non-linear, etc.)
Linear, sine wave, user-defined...
Breach Growth Details

- Dimensions grow linearly (or use other function)
  - Depth and width for overtopping
  - Height and width for piping
  - Width only during breach widening
- Breach width $\rightarrow t$
- Breach area $\rightarrow t^2$
- Assuming minimal reservoir drawdown during breach
  $Q \rightarrow t^{2.5}$ during overtopping / deepening (post-piping)
  $Q \rightarrow t^2$ during piping
  $Q \rightarrow t$ during widening
Breach Growth - Future

- HEC-RAS 5.0 will make sine function default
- Non-linear growth rates have not been common until now
  - Most breach parameter prediction equations were developed with linear growth of breach dimensions as the modeling norm
Linear vs. Sine

- Practical difference is usually small
  - exponential growth of Q accentuated in early stages
  - more gradual tapering of Q growth at end
Other Parameters

- Breach initiation time (pre-breach time) is valuable to know if modeling objective is to predict warning time.
- There are no equations that predict this.

- Increased outflow and/or erosion begin (detectable and sufficient to create heightened awareness of potential for dam failure).
- Breach has enlarged to its maximum size.
- Breach initiation time, \( t_i \)
- HEC-RAS “Full Formation Time”
- Potential warning time immediately below dam.
- Peak outflow occurs.
- Active erosion front reaches upstream face of dam. Enlargement of the breach at the point of hydraulic control begins.
- Erosion progressively slows and stops as reservoir drains; breach sides can slump as water level draws down.
- Breach outflow hydrograph.
- Reservoir drawdown curve.
The Other Parameter...

- Predict breach outflow directly as a “parameter” of the breach
Breach Parameter Equations

• Breach parameters could be predicted with...
  – Equations developed analytically
  – Regression relations developed by analyzing results of numerical or analytical model runs spanning a range of conditions
  – Regression relations developed from results of laboratory tests

• Most breach parameter equations were developed using data from real failures
Regression-Based Methods

- Rapid, economical for appraisal-level
  - (but have been used for much more than just appraisal-level work)
- Low complexity (compared to physically-based models)
- Simple data needs
  - Dam height, reservoir size
  - Sometimes the dam type or failure mode
- 2001 FEMA-sponsored workshop suggested trying to incorporate erodibility, dam type, and failure mode
# Peak Flow Equations

<table>
<thead>
<tr>
<th>Relation</th>
<th>Cases</th>
<th>H</th>
<th>S</th>
<th>H*S</th>
<th>dam type</th>
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<td>Xu &amp; Zhang (2009)</td>
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<td>Pierce et al. (2010)</td>
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- 2004 analysis showed Froehlich (1995) to have lowest uncertainty, ±0.32 log cycles
  - Others in range ±0.5 to ±1.0 log cycles
Breach Width Equations

- 2004 analysis showed Von Thun & Gillette (1990), Froehlich (1995) and USBR (1988) perform similarly, uncertainties of about ±0.35 to 0.4 log cycles
  - MacDonald & Langridge-Monopolis (1984) about ±0.8 log cycles
Breach Shape Equations

- Few equations available
- Breach tests suggest slopes are often near vertical during an event

<table>
<thead>
<tr>
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<th>Dam thickness</th>
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<td>1.0 non-cohesive; 0.33-1.0 cohesive</td>
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<td>1.4 overtop; 0.9 otherwise</td>
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<td>Froehlich (2008)</td>
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<td>1.0 overtop; 0.7 otherwise</td>
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<tr>
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<td>49</td>
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<td>X X</td>
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<tr>
<td>implied by equations for breach top width, average width, depth</td>
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<td>X X</td>
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</tbody>
</table>
• 2004 analysis showed Froehlich (1995) to have lowest uncertainty (± 2/3 log cycles)
• Other methods, approx. ± 1 log cycle
• Froehlich (2008) probably best choice today
• Xu & Zhang (2009) equation overpredicts $t_f$
Newer Equations

• Froehlich (2008) breach parameter equations are similar to those from 1995, with more case studies added
  – Best available at the time of their publication

• Pierce et al. (2010) developed peak flow equations with several functional forms using a larger data set (87 dams)
  \[ Q = f(H) \quad Q = f(S) \quad Q = f(H \times S) \quad Q = f(H, S) \]
  – Similar in form to previous equations
  – Not yet tested on equal footing vs. older equations
Thornton et al. (2011) Equations

- Added two other input parameters
  - Embankment thickness, $W$
  - Embankment length, $L$
  \[ Q = f(H, S, W) \quad Q = f(H, S, L) \]

- Started with Pierce’s database (87 dams), but reduced to 25 / 14 dams to add the extra parameters
Thornton et al. (2011)

Froehlich peak-flow equation $Q = f(H, S)$

Thornton equation $Q = f(H, S, L)$

- Correlation appears very good for the relation that uses L, but why?
Effect of Embankment Length?

• Length probably has correlation to storage volume (which is already in other equations)
  – Why does it further aid peak outflow prediction?
• Reservoir flow dynamics
  – Large storage volume in a wide reservoir can easily contribute to breach outflow
  – Large storage volume in a long reservoir cannot
• Taum Sauk reservoir was a 2000 m ring dike
  – How did the extra length of that embankment contribute to a large peak outflow?
Importance of erodibility...

USDA-ARS Tests

Figure 4. Embankment widening test showing initial notch width.

Figure 5. Photographic measurements of erosion width.
Erosion rates vary by orders of magnitude

Hanson and Hunt (2007)

Hunt et al. (2005)
**Xu & Zhang (2009)**

Related 5 dimensionless breach parameters to 5 dimensionless control variables (inputs)

<table>
<thead>
<tr>
<th>Breaching parameters</th>
<th>Control variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breach depth</td>
<td>$Y_1 = H_b / H_d$</td>
</tr>
<tr>
<td>Breach top width</td>
<td>$Y_2 = B_t / H_b$</td>
</tr>
<tr>
<td>Average breach width</td>
<td>$Y_3 = B_{ave} / H_b$</td>
</tr>
<tr>
<td>Peak outflow rate</td>
<td>$Y_4 = Q_p / \sqrt{gV_w^{5/3}}$</td>
</tr>
<tr>
<td>Failure time</td>
<td>$Y_5 = T_f / T_r$</td>
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</tbody>
</table>

Failure mode
- overtopping $X_{41}$ 1(e) 0(1)
- seepage erosion/piping 0(1) 1(e)

Dam erodibility
- high erodibility $X_{51}$ 1(e) 0(1) 0(1)
- medium erodibility 0(1) 1(e) 0(1)
- low erodibility 0(1) 0(1) 1(e)

Note: aValues for additive regression analysis;
bValues for multiplicative regression analysis.

$H_r = 15 \text{ m}; T_r = 1 \text{ hour.}$
Xu & Zhang (2009)

- Regression analysis used 75 dam failures with erodibility categories determined subjectively *(high, medium, low)*
  - 41 prior studied failures (mostly U.S.)
  - 34 newly studied failures (32 from China)
- Erodibility had the most influence on dimensionless breach parameters

(Dam height is still most important in the dimensional world)
Questions

• Newly included dam failures are mostly described only in Chinese-language references...difficult to validate data

• Are assigned erodibility categories appropriate for each dam?
  – Source references and justification not given for each dam’s erodibility classification
  – Xu’s thesis (2010) did not give further details

• Why are predicted failure times longer than those given by previous equations?
NRC-Commissioned Study

- Review the Xu & Zhang (2009) equations focusing on
  - erodibility classifications
  - failure times
- Document data sources and rationale
Reviewing Data

• Xu & Zhang (2009) data
  – 41 prior studied failures (mostly U.S.)
• 40 additional failures from various sources
• Consulted many primary documents on individual dams
  – Dam failure forensic reports
  – USGS reports (usually flood-focused)
  – Magazine and journal articles (Engineering News-Record 1902-present, ASCE Trans., Civil Engineering, International Journal of Hydropower and Dams, etc.)
Erodibility

- Xu and Zhang (2009) described factors considered, but did not provide specific justification or references to support each dam’s erodibility category
  - Rockfill and clay = medium to low erodibility
  - Sand and silt = high to medium erodibility
  - Compaction conditions
  - Construction era, type of equipment
    - China 1950’s --- very little mechanical compaction equipment
  - Cross-sectional geometry and slope protection
  - Observed breach size and failure time
Erodibility Conclusion

- I examined cases individually and documented reasons for assigning erodibility categories
- Concluded that erodibility categories were generally reasonable
  - A few cases in which I might have chosen differently, but no bias
Failure Times

- In many cases, Xu and Zhang’s failure times were longer than the breach formation time given in previous compilations or longer than the breach formation time suggested by narrative descriptions of dam failures.
- Often seemed to be the sum of breach formation time and breach initiation time.
## Teton Dam – Failure Time?

<table>
<thead>
<tr>
<th>Reference</th>
<th>Time (hr)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xu &amp; Zhang (2009)</td>
<td>4</td>
<td>Failure time</td>
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<tr>
<td>Froehlich (2008)</td>
<td>1.25</td>
<td>Breach formation time</td>
</tr>
</tbody>
</table>

![Graph showing flow discharge over time]

**Legend**
- A: Outflow rapidly increased
- B: Dam crest collapsed
- C: Peak outflow
- D: Breach fully formed
Teton

- Attempted to model the Teton failure in HEC-RAS using conservatively large breach dimensions and Xu and Zhang’s 4 hr failure time
  - Peak outflow about 1,060,000 cfs
  - Much lower than 2,300,000 cfs determined by USGS using indirect measurement techniques
- Modeling by multiple other investigators suggests Froehlich’s 1.25 hr breach formation time is credible
Evaluation of Xu/Zhang Equations

- Compared predicted vs. observed breach parameters for dam failures with VERIFIED erodibility
- Also compared to performance of previously established equations
- Most parameters are well-predicted by Xu & Zhang (2009) equations (breach height, breach width, peak outflow)
- Failure time (breach formation time) is not
Xu & Zhang (2009) 'Best' average breach width

Coefficient of determination = 0.83

Froehlich (2008) avg breach width

Coefficient of determination = 0.68

RECLAMATION
Xu and Zhang (2009) predicted failure times are greater than or equal to observed breach formation time for every case.
Primary Conclusions

- Breach height, breach width, and peak outflow equations perform well
  - Generally a little better than other available equations
  - Erodibility was a valuable input, even though it had to be assigned subjectively
  - Xu & Zhang’s erodibility categories seemed reasonable

- The Xu & Zhang (2009) failure time equation **cannot be applied with any confidence**
  - It is based on data that represent an undefined mix of breach formation times and total breach times (initiation + formation)
  - Froehlich (2008) is still the best available breach formation time equation
Application to Low Erodibility Dams

• There were too few cases to justify developing equations specifically for “low erodibility”

• Influence of “low erodibility” is dramatic in peak outflow and failure time equations
  – More so than “high erodibility”
Low Erodibility Dams

- 7 low erodibility dams cited by Xu and Zhang (2009)
- 4 in China
- Frankfurt Dam (Germany, 1977)
  - No materials information found, no idea of compaction state
- Oros Dam (Brazil, 1960)
  - Peak outflow unreliable (6:1 ratio between contradictory values)
- Winston Dam (USA, 1912)
  - Narrative description of embankment said it contained very poor soils, and observed failure time was unreliable
- Oros is the only useful case, and only for breach width and failure time
- This is unsufficient data to justify the large influence that low erodibility has in the prediction equations
Further Developments

- Dr. Xu and associates have been working to address these issues and produced a conference paper for HydroVision 2014 with revised breach parameter equations.
Toward Objective Methods for Erodibility

- Lab/field tests to determine erodibility parameters
  - Submerged jet test
  - Hole erosion test
  - Flume-based tests (Erosion Function Apparatus, SEDFLUME)
- 5- to 6-tier classification systems have been associated with each of these tests...could try to simplify to 3 tiers
- Classification tables based on %clay, compaction energy and compaction water content (e.g., Hanson et al. 2010)
What materials are in our dams?

| Submerged jet test, $k_d$ values (ft / hr / psf) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 100             | 10              | 1               | 0.1             | 0.01            | 0.001           |

| Hole erosion test, $I_{HET}$ |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1                           | 2               | 3               | 4               | 5               | 6               |

RECLAMATION
Future Dam Failures

• Perform field or lab TESTING to evaluate erodibility quantitatively
• Document detailed soil properties
• Investigate construction history to determine compaction conditions
Physically-Based Models

• Can be used to develop breach description vs. time, and/or an outflow hydrograph

• Advantages
  – Provide means for estimating breach initiation time
  – May give a good basis for using a non-linear or user-defined function for growth of breach dimensions
Models to be presented...

- **GeoDam-BREACH**
  - Geospatial Dam Break, Rapid EAP, Consequences, and Hazards
  - FEMA toolset that utilizes SMPDBK with output presented in a geospatial environment
  - Peak flow estimated with analytical equation

- **WinDAM**
  - Physically-based breach model for overtopping of homogeneous cohesive embankments
  - Focus on headcut erosion mechanics
  - Upcoming capability to model piping failures
More models...

- **HR BREACH (EMBREA)**
  - Physically-based breach model for overtopping and piping of homogeneous and zoned embankments
  - AREBA (A Rapid Embankment Breach Assessment)
    - Simplified, rapid model for homogeneous embankments

- **HEC-HMS and HEC-RAS**
  - Dam-break enabled flood routing models that use breach parameters
  - HMS is 1-D, level-pool. RAS simulates reservoir dynamics and has 2-D capability coming in v. 5.0.
More models...

- FLDWAV / SMPDBK / Geo-SMPDBK / BREACH
  - Models originally developed by National Weather Service 1980s
  - FLDWAV is dam-break enabled flood routing model that uses breach parameters
  - SMPDBK – analytical
  - GeoSMPDBK - a GIS-based tool for rapid development of SMPDBK models
  - BREACH is a physically-based breach model using traditional sediment transport concepts
Even more models...

- **DSS-WISE**
  - A web-based dam-break flood inundation analysis tool using *breach parameters*
  - 2-D flood propagation over landscape
- **MIKE software**
  - 1-D and 2-D dam-break enabled flood routing models using *breach parameters*
Finally...

- **XP-SWMM**
  - 1-D and 2-D flood routing model with dam-break capabilities

- **Flo-2D**
  - 2-D dam-break enabled flood routing model with *physically-based* breach simulation
Questions?