Simulating Levee Erosion with Physical Modeling Validation

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Outline

- Motivation
- Background
  - Related Research
- Multidisciplinary Research Team
- Experimental Setup
- Experimental Procedure
  - Data Collection
  - Visualization
- Findings
- Conclusions and Future Considerations
- Acknowledgement

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Motivation

- Past failures have prompted the study of erosion on earthen embankments
  - Teton Dam (1976)
  - New Orleans' Levees after Hurricane Katrina (2005)
- Determine time required for erosion processes to occur
- Understand rill and gully initiation and propagation
- Visualize using software
- Create digital simulations
- Increase estimation capabilities

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Background

- Levees are designed to protect areas adjacent to bodies of water from flooding
- Poor design/construction can lead to disasters
- Multiple failure mechanisms when subjected to water loading
  - Overtopping
  - Surface Erosion
  - Internal Erosion
  - Instabilities within embankment or foundation soils

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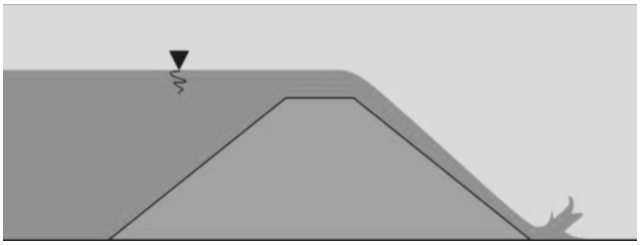
Background



- Uncontrolled flow of water over or around an embankment
- Flowing water will erode soil on landside slope

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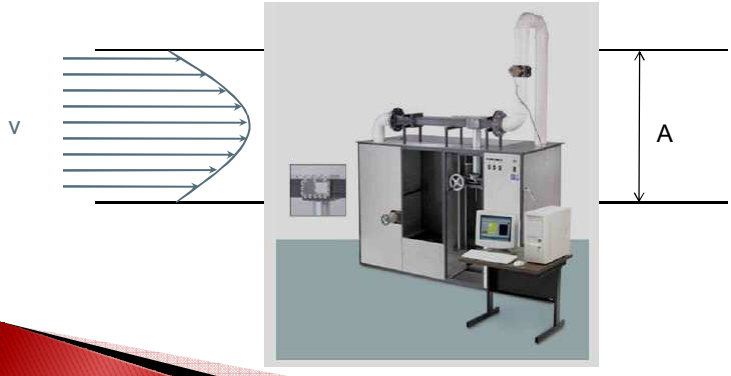
Related Research

- Briaud (2008); extensive research on erosion characteristics of different soils
- Use of Erodibility Function Apparatus



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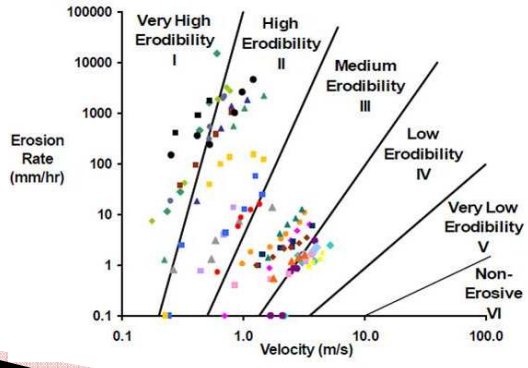
Related Research

- Soil Erodibility
  - Relationship between water velocity and rate of erosion experienced by soil
- Cohesive: Low Erodibility
- Granular: High Erodibility



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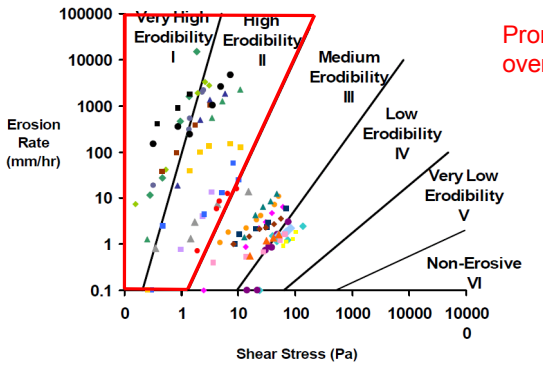
Related Research

- Soil erodibility is more accurately plotted versus hydraulic shear stress



Prone to failure by overtopping

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Multidisciplinary Research Team

- Three departments are involved with the levee erosion research:
  - Civil & Environmental Engineering
  - Computer Science
  - Electrical, Computer and Systems Engineering
- Each member has unique roles that partially overlap with roles of other members
  - Produces new insights into previously studied areas

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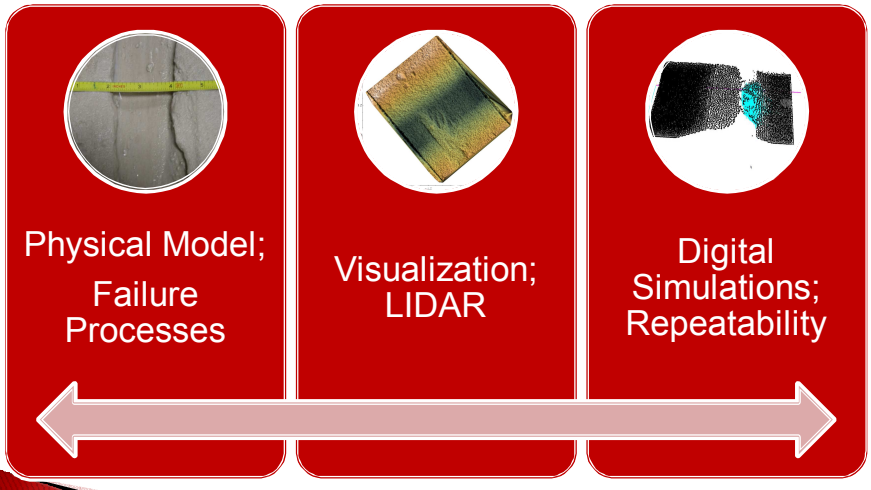
Multidisciplinary Research Team



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Collaboration

Physical model, post-laboratory erosion simulation

+

3D Laser Range Scanner

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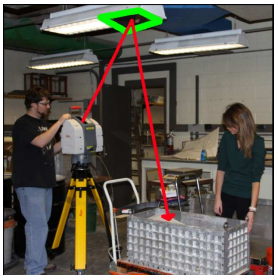
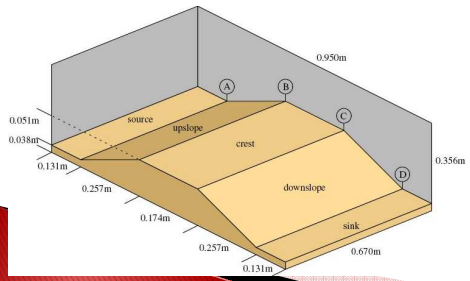
Physical Experiments

- Purpose: validation
- On a small-scale levee
- Scans
- Videos





Experimental Setup

- Model levees were constructed in an aluminum box (36” L x 24” W x 14” H)
- Slopes were 1V:5H
- Different soils have been tested
  - Medium-well graded sand
  - Nevada 90 sand
  - Nevada 90 sand – Kaolin clay mixture
- Testing performed with and without low-permeability core
- Water supply on waterside, drain on landside of model

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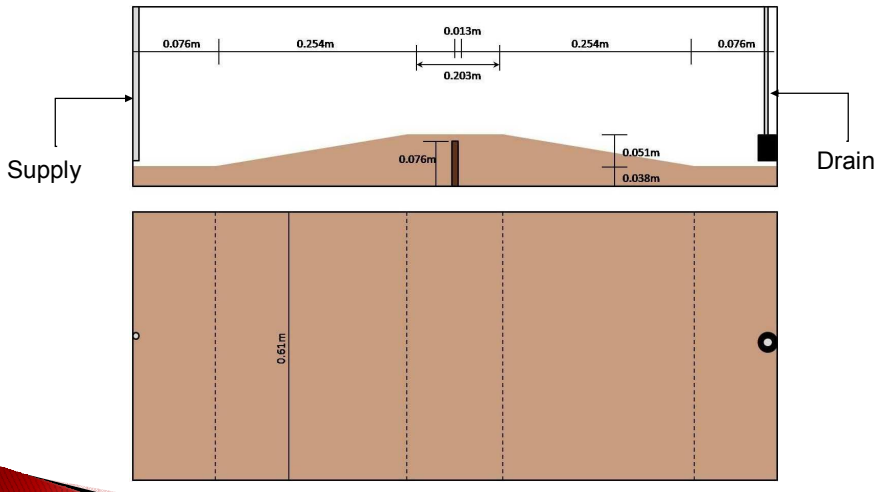
Experimental Setup



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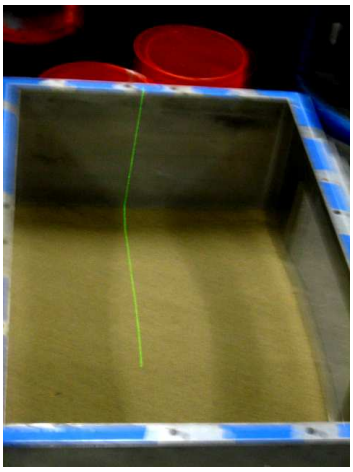
Data Collection

- Laser beam emitted, scanner rotates and scans model at incremental rotations
- Collects “slices” of elevation data from model
- Data collected as a “point cloud”
- Data is then aligned to an X-Y plane
- A grid where each cell contains an array of soil layers with heights and depths results



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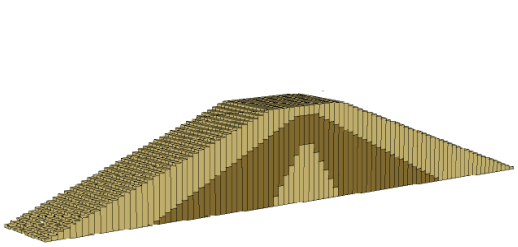
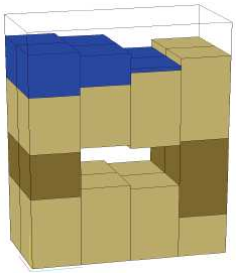
Our Data Structure

- Segmented Height Field
  - Multiple layers
  - Robust
  - Supports overhangs and air pockets

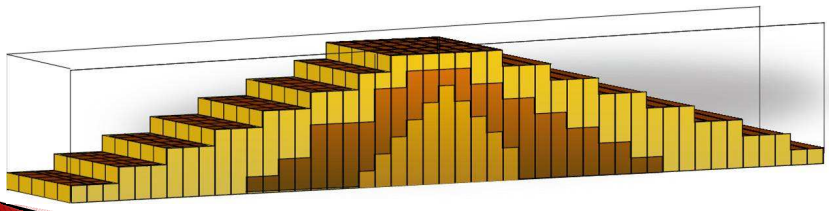




From [Stuetzle et al., 2009]

Visualization

- Data from scanner is loaded into data structure
- Developed the Segmented Height Field data structure
- Calculation of eroded volumes, channel widths, channel depths, etc.



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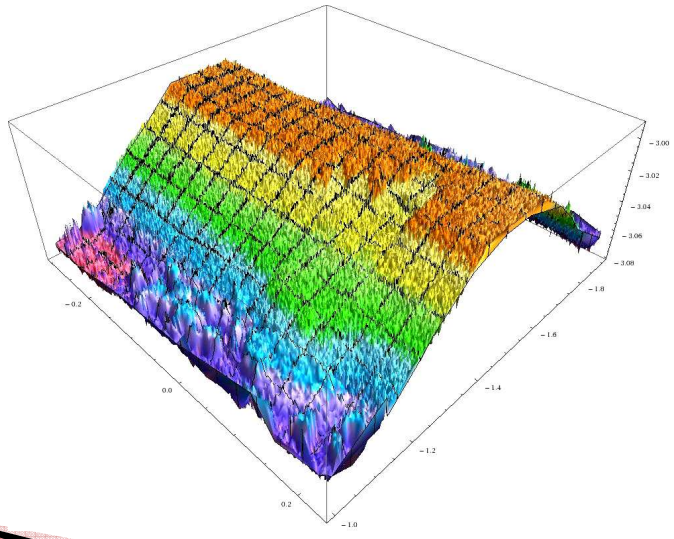
Visualization



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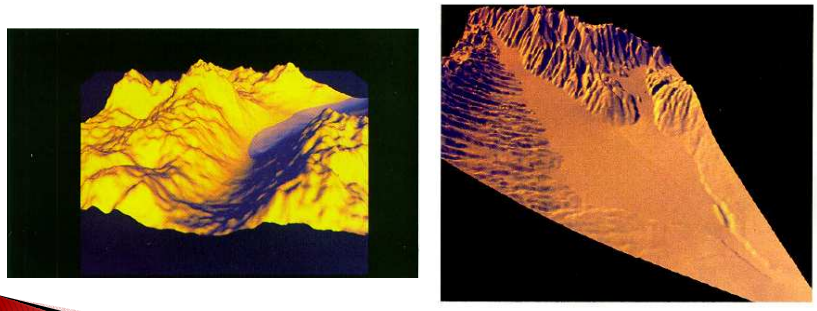
First Erosion Simulation Technique

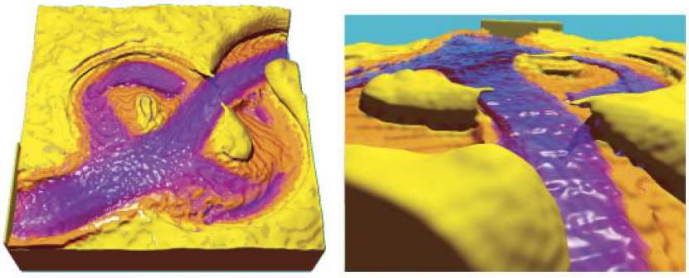
- Terrain represented by height fields
- Soil and water motion calculated by terrain gradient



From [Musgrave et al., 1989]

Erosion Simulation on Grid

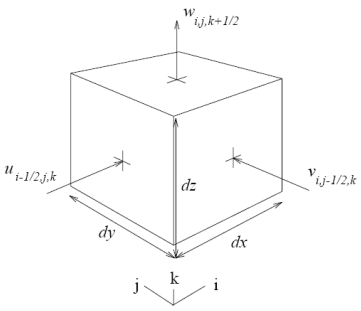
- Fluid and erosion simulation coupled on a 3D grid
- Sediment transported based on fluid simulation results
- Low efficiency

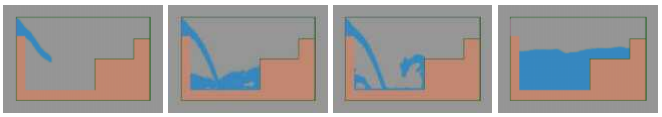


From [Benes et al., 2006]

Full 3-D Simulation

- Marker-And-Cell (MAC) method
  - Navier-Stokes equations on a grid
  - Each cell with physical fields
  - Massless marker particles





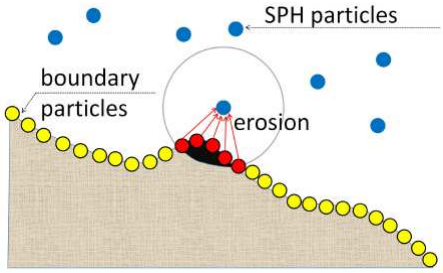
From Foster and Metaxas, 1996

Features of SPH

- State of the system represented by particles
- Based on interpolation theory
- Handles objects with large deformation or mixed by different materials
- Save memory on void regions
- SPH particles
  - Carriers of physical information
  - Trackers of fluid surface

Erosion Simulation with SPH

- Terrain modeled as height field
- Fluid simulated by SPH
- Terrain surface is modeled as a triangular mesh

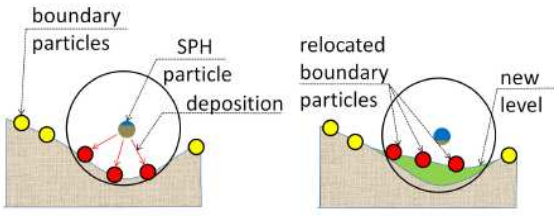


From [Kristof et al, 2009]

Erosion Simulation with SPH (Cont.)

- Erosion rate ε is calculated by $\varepsilon = K_\varepsilon(\tau - \tau_c)$, where is K_ε is erosion strength, τ is shear stress and τ_c is critical shear stress.
- Two-step terrain modification:

1. Erosion and deposition mass on each boundary particle is calculated
2. The height change of a triangle is calculated by the total mass change of all particles in its area



From [Kristof et al., 2009]

Essential formulations of SPH

- Kernel approximation:

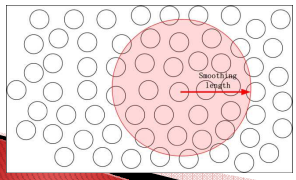
$$f(x) \approx \int_{\Omega} f(x')W(x-x',h)dx'$$

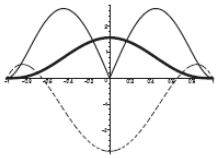
f is a field function defined in Ω, *x* is a point in Ω, *W* is a kernel function and *h* is the smoothing length.

- Particle Approximation:

$$f(x) \approx \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(x_j)W(x-x_j,h)$$

where *x* is the position of a point, X_j(j=1,2…,n) are positions of the particles neighboring *X*, m_j is the mass and ρ_j is the density.

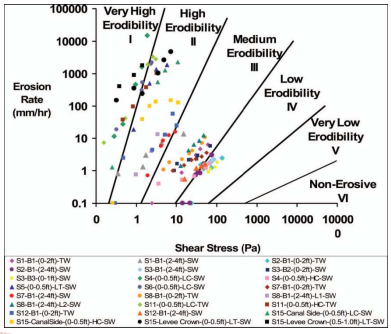




From [Muller et al., 2003]

Comparison with Our Method

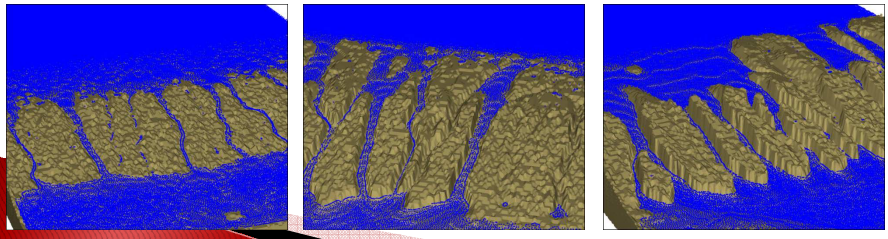
- Difference of our method from method of Kristof et al.:
  - Segmented height field
  - Terrain represented by particles
  - Erosion model by Briaud & Chen [Briaud&Chen, 2006]



From [Briaud and Chen, 2006]

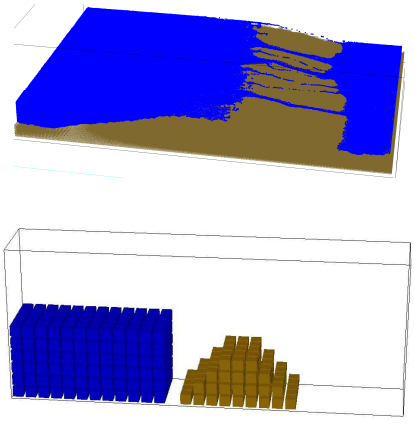
Simulation Setup

- Spatial resolution:
  - Soil particle spacing: 0.003m (2,500,000 particles)
  - Water particle spacing: 0.004m (450,000 particles)
- Smoothing length: 0.008m
- Time step size: 0.001 seconds
- Time of running a 10-minute simulation: more than a week (depending on the machine)

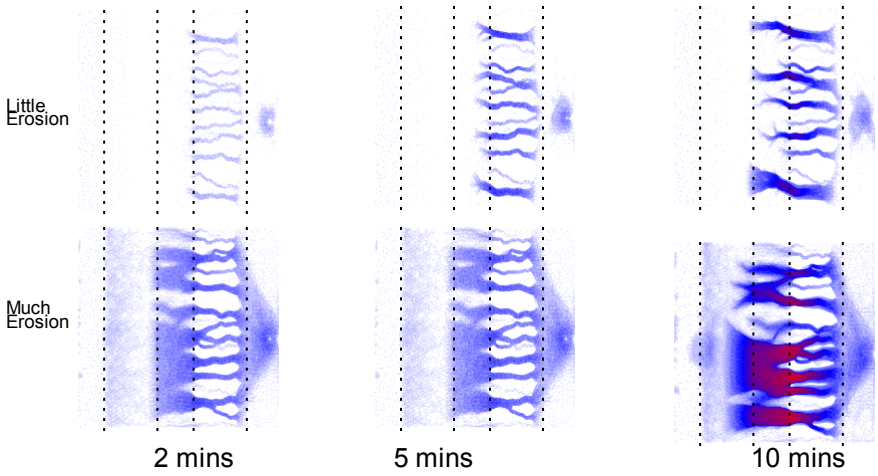


Computer Simulation

- Computer simulation
  - Pros:
    - Various scales
    - Whole process
    - Details of gully
  - Difficulty:
    - Accuracy
    - Efficiency

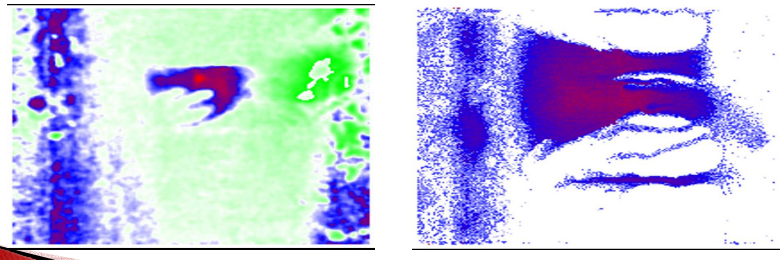


Erosion Depth



Sediment and Deposition

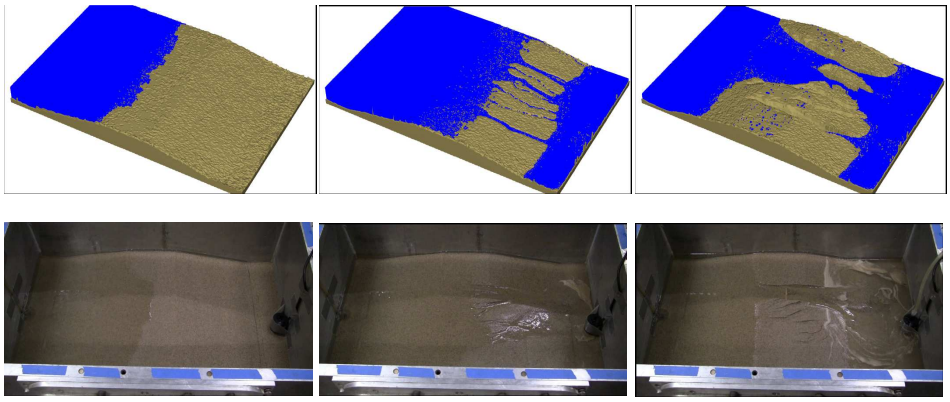
- Sediment transportation and deposition
- Deposition cannot be ignored in small-scale experiments
- The method in [Kristof et al., 2009] as starting point



scanned result

simulation results

Comparison and Validation



Before overtopping overtopping | 2 mins after overtopping | 10 mins after

Findings

- Models using a core did not fully breach unless a very low Q was used
  - Flow rate impacts rill characteristics
- Sand models eroded grain-by-grain
- Sand-clay models eroded in larger clumped masses
- Models with a core saturated more slowly, eroded more slowly
- Clay content effects erosion and breach failure times

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Future Considerations

- Continued sand-clay mixture testing
- Centrifuge testing
- Flume testing
- Different soils
- Reinforcement/armoring
- Changes in levee geometry
- Digital simulation

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Reverse Engineering

- Reverse engineering
  - Helpful for people to look at the erosion process
  - Not possible to record the process
  - Our goal is to reversely simulate the erosion process based on the shape of the eroded levee

Acknowledgment

- This research is supported by the National Science Foundation grant CMMI-0835762

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Questions?