Prototype Measurements of Rock Block Erosion: Implications for Dam Foundation and Spillway Erodibility Assessment

Michael F. George
BGC Engineering, Inc. (formerly Univ. of California – Berkeley)

Nicholas Sitar
Dept. of Civil & Environmental Engineering – University of California at Berkeley

Motivation

- Scour is important process for civil infrastructure reliability
- Limited data for hydraulic loads and displacement response of 3D blocks
- Simplified block geometries - rectangular (2D), cubic (3D)
- Examine influence of joint orientation on 3D block erodibility

Dam Overtopping

Unlined tunnel

Rock spillway /channel
Model (Lab) and Prototype (Field) Experiments

• Prototype
  – Actual field conditions
  – Dams/spillways make good field experiment sites -> regulated flows
  – Actively eroding rock spillway channel in Northern California
  – Installed 2 artificial rock blocks
  – High pay-off, unique data
  – Great idea!

• Model
  – Test a variety of scenarios
  – Idealized conditions
  – “Everybody’s doing it”
  – More “reliable” results
Prototype Experiment Site - Spaulding Dam

~ Initial conditions (1920's)

Present day
Instrumented Rock Blocks
Artificial Rock Blocks...High & Dry...
3D Instrumented Block in a Flume

- Physical hydraulic model testing setup
- Modeled scenarios
  - 9 discharges
  - High/low turbulence
  - 3 block protrusion heights
  - 13 block rotation angles
- Instrumentation
  - Block pressure (12)
  - Block displacement (3)
  - 3D flow velocity
  - Flow depth
- Goal:
  - Comprehensive, high resolution data set
Model Flume – Block Response – 3 Modes

- **Mode 1**
  - LOW kinematic resist.
  - high/low $Tu$
  - gradual displacement

- **Mode 2**
  - HIGH kinematic resist.
  - low $Tu$
  - gradual displacement

- **Mode 3**
  - HIGH kinematic resist.
  - high $Tu$
  - impulse displacement
Model Flume – Block Response – Displacement Vector

Mode 1

Mode 2
Model Flume – Block Theory Prediction

Block erodibility threshold

- Maximum velocity tested
- Block theory prediction - low $T_u$
- Block theory prediction - high $T_u$

Meanflow velocity, $u_x$ (m/s)

- Flow direction

Block mold rotation angle, $\psi$ (deg.)

Low Turb

High Turb

Mode 1

low $T_u$, $h = 1.7$ cm

high $T_u$, $h = 1.7$ cm

Berkeley
March 5&6 Event - PG&E Site Visit

March 6, 2016
8 am
4,430 cfs

Block 2 (eroded)
Block 1
PG&E Site Visit

March 6, 2016
8 am
4,430 cfs
Event Hydrograph

Spaulding Dam No. 2 - March 2016 Spill Event

- Large Gates
- Small Gates
- Total

- PG&E Site Visit
  March 6 (8AM)
- Block 2 Eroded
  March 5 (~3AM)
- UC-Berkeley Site Visit
  March 12 (10AM)
UC-Berkeley Site Visit

June 8, 2016

Block 2 (eroded)

Block 1
Flow Hydraulics – Particle Image Velocimetry

Video from: March 12, 2016
10 am
1,073 cfs

Scale video using LiDAR point cloud

\[ u = 10.3 \text{ m/s} \]
\[ Tu = 19\% \]
**Block Displacement**

Displacement Time Series

- **Initial block wetting**
- **Gradual displacement, except...resonance, bad data?**
- **Removal**

Likely Mode 1 or Mode 2
Block Displacement Vector

Displacement (mm)

Displacement magnitude: 4pm, 6pm, 8pm, 10pm, 12am, 2am, 4am

3/5, 8pm – Oriented along $i_{12}$

3/6, 2:54am – Oriented along $i_{12}$
Block LE Graphical Solution

LIMIT EQUILIBRIUM DIAGRAM

Average Resultant Force Vector, R, Orientation

Whole sphere stereonet, lower hemisphere projection
Had to use measured pressure on free surface face due to complex flow conditions
Block Theory Prediction

Block Erodibility Threshold as a function of flow direction

- Predicted critical velocity ($Tu = 7\%$, max tested), $u = 14.2$ to $16.9$ m/s
- Actual critical velocity ($Tu \sim 13\%$), $u = 16.3$ m/s (crude estimate)
Implications for Erodibility Analysis

• Prototype block showed similar response to model
  – “Expected” if models obey proper laws of similitude

• Idealized model geometries cause difficulty extrapolating to field conditions
  – Hydraulic forces very dependent on geometry
  – Small details matter (protrusions, face orientations, etc)
  – Hard to develop general solutions

• Block theory approach yields good promise to incorporating 3D site geologic structure for various polyhedral block shapes

• 3D numerical computational fluid dynamics (CFD) modeling may eventually be adequate to estimate erosive capacities for complex geometries.
Questions?
Pressure & Disp. Time Series

Timeline of Events

- 2:20 am – Trouble w/ sensors
- 2:26 am – All sensor malfunction or impulse to block (~ 13 s duration)
- 3:04 am – Sensor cables broken
Spectral Density ($S_{xx}$)

3/5, 10pm – Response ~ 10 Hz -> Not observed on Free Face -> Resonance of pressures within joints?

No other peaks show this response
Block Displacement

Displacement Time Series

- Gradual displacement, except...resonance, bad data?
- Initial block wetting
- Likely Mode 1 or Mode 2
**Block Displacement Vector**

Displacement (mm)

3/5, 8pm – Oriented along $i_{12}$

3/5, 10pm – Oriented along $f_2$
Block Displacement Vector

Displacement magnitude

3/6, 2:54am – Oriented along $i_{12}$

3/6, 2:57am – Removal
Block LE Solution

Instantaneous Resultant Force Vector, \( \mathbf{R} \), Orientation

2:17am to 2:19am

Whole sphere stereonet, lower hemisphere projection