Stream Power and Scour of Weak Rock and Cemented Earth Materials – an Update

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I-90 at Schoharie Creek, New York

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FHWA mandate for scour-critical bridges to be evaluated
Research Objectives

- Develop a methodology for determining
  - Design Scour Depth
  - Time-Rate of Scour
- Develop design and construction guidelines for applying the methodology

- NCHRP Project 24-29 → NCHRP Report 717 (2012)
- Jeff Keaton, Su Mishra, and Paul Clopper
General Soil and Rock Application

- Erodibility Index Method; Annandale (2006)

Water flow with peak stream power at the channel

Channel bottom Geotechnical profile expressed in terms of power
Scour-Resistant Rock - material likely to withstand flowing water without substantial scour; generally consistent with concrete because concrete …
- looks like rock
- is strong enough to support loads
- does not slake
- remains in place when large blocks are subjected to relatively swiftly flowing water
- has been used in engineering applications for scour protection

Rock material not as good as concrete might be scour-resistant;

All rock erodes, the question is ‘how fast?’
Reality indicates that it is a ‘rock-water interaction’ problem
Rock Scour Modes

- Identify Relevant Scour Modes
- Dismiss Non-relevant Modes

Regional Climate, Geology, Topography Data; Local Geology, Topography Data

Hydrology and Hydraulics
Slope, Profile, Velocity, Depth
Shear Stress, Stream Power

Watershed Factors
Bedload (size, composition)
Knickpoints (size, location)
Channel Conditions (continuously wet, partial drying cycles, complete drying cycles)

Time Factor
Time Between Flood Events (chemical and physical weathering preparing rock for next scour event)

Soluble Rock Concern?

yes
Formations Containing Soluble Minerals; Geologic Evidence of Filled Solution Cavities

no

Cavitation Concern?

yes
Geologic Evidence of Past Cavitation; Hydraulic Conditions Met or Exceeded

no

Jointed, Fractured Rock?

yes
Blocky Condition, Rock Slabs, Irregular Channel Bed, Headcut and Plunge Pool

no

Degradable Rock?

yes
Abraded, Sculpted, and Pitted Rock Surfaces; Slaked Rock Material

no

Bridge Factors
Construction Methods; Blast Damage; Foundation Type, Location, and Depth
Durable Rock Blocks

- Pier Scour

Erik Bollaert, AquaVision Engineering

Bridge Pier (turbulence generator)

Hancock et al., 1998

Threshold Velocity for Plucking (ft/s)

Block Thickness (ft)

Inclined joints; no protrusion
Vertical joints; no protrusion
Inclined joints; large protrusion
Vertical joints; large protrusion

No angle of attack

Flow

Head = \( \frac{v^2}{2g} + \frac{P_1}{\gamma_w g} \)

\( F_L = (P_2 - P_1) \) xy

\( F_N = (\gamma_f - \gamma_w) g \) xyz

Head = \( P_2 \)

Initial lift when \( F_L > F_N \)
Degradable Rock Scour

Rock scour is a "rock-water interaction" problem
I-10 Bridge Over Chipola River

Rotating Erosion Test Apparatus (RETA)

Oligocene marine dolomitic limestone
SR-22 Bridge Over Mill Creek

Oligocene marine siltstone

Water Flow

Water Flow

SR-22 over Mill Creek, Polk County, Oregon
I-90 Bridge Schoharie Creek

Quaternary ice-contact stratified drift

Schoharie Creek Gage
Paleozoic marine sandstone
SR-262 Montezuma Creek

1946 1979 1984

Original slope: 0.0037
Cutoff slope: 0.0187

Jurassic fluvial sandstone/claystone

1984
SR-273 Bridge Over Sacramento River

Cretaceous marine siltstone

California DOT core samples
Modified Slake Durability Test

ASTM D4644 -08 Standard Test Method for Slake Durability of Shales and Similar Weak Rocks

Slake durability equipment used to perform continuous abrasion test modified from Dickenson and Baillie (1999)
Modified Slake Durability Test

Average mass during test increment (N, lb) [normalized to 500 g initial mass]

Circumference x rpm x time of rotation = equivalent distance traveled (m, ft)

60-min (3600-s) test increment (s)

Sample residence area (m², ft²)

N-m = J; J/s = W → W/m² [= ft-lb/s/ft²]

Unit weight of rock material (N/m³, lb/ft³)

Sample loss N/N/m³, lb/lb/ft³ = m³, ft³ → m, ft (normalized)
Modified Slake Durability Test

Sacramento River Siltstone Samples
Geotechnical Scour Number

\[ y = -7.55 \times 10^{-6} + 1.90 \times 10^{-4} x \]

\( n = 16; \ r^2 = 0.799 \)

95% Confidence
95% Prediction

Equivalent Scour Depth (ft x 0.0001)

Equivalent Stream Power (ft-lb/s/ft²)

- Sacramento Siltstone Sample 1
- Sacramento Siltstone Sample 2

0.000217 ft/unit of power

0.00019 ft/unit of power
Geotechnical Scour Number
Estimating Erodible Rock Durability and Geotechnical Parameters for Scour Analysis

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Armor Stone Quality Test

Cumulative Equivalent Hourly Stream Power (MW m\(^{-2}\))

Fractional Weight Remaining, Wt/Wt\(_0\)^{-1}

Time, t (revolutions x 1000)

Armor Stone Quality
- Excellent
- Good
- Marginal 1
- Marginal 2
- Poor 1
- Poor 2

Equivalent Hourly Scour Depth (m x 10\(^{-4}\))

Revolution of Armor Stone Abrasion Mill

Equivalent Hourly Stream Power (W m\(^{-2}\))

Abrasion resistance index

GSN = 5E-07 m (W m\(^{-2}\))^{-1}

k\(_S\) = constant
Natural Gas Pipeline, Pima Co, AZ
Weakly Cemented Alluvial Fan Deposits

Durable grains accumulating in test basket

Graph showing relationship between equivalent hourly stream power and scour depth.
Weakly Cemented Alluvial Fan Deposits
Rock-Water Interaction

- Equivalent scour depth for Geotechnical Scour Number from
  - 15-min measurement → 0.03 ft
  - 10-min calculation → 0.04 ft
  - 5-min calculation → 0.08 ft
  - 1-min calculation → 0.4 ft

Hourly stream power

40.347 ft-lb/s/ft²
Degradable vs. Durable Materials
Degradable vs. Durable Materials

NCHRP Data

- CS1
- CS2
- ST1*
- ST2*
- LS1
- LS2
- ST1
- ST2

Equivalent hourly scour depth (ft x 0.0001)

Equivalent hourly stream power (ft-lbf/s/ft2)
Degradable vs. Durable Materials

NCHRP Data

Equivalent hourly scour depth (ft × 0.00001)

Equivalent hourly stream power (ft-lbf/s/ft²)

- CS1
- CS2
- ST1*
- ST2*
- LS1
- LS2
- ST1
- ST2

- 15-min test cycles
- 6.539E-04
- 10-min cycle calculation
- 9.808E-04
- 5-min cycle calculation
- 1.962E-03
- 1-min cycle calculation
- 9.808E-03
Future Research

- Flume tests for comparison to modified slake durability tests for Geotechnical Scour Number
- Further consideration of accumulating durable grains in test basket
- More bridges with measured cross sections showing progressive scour
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