Erosion of Rock and Soil

Best Practices in Dam and Levee Safety Risk Analysis

Section D – Embankments and Foundations

Chapter D-1

Last modified July 2018, presented July 2019
Outline

• Objectives
• Key Concepts
• Erosion Process
• Rock Erosion Considerations
• Soil Erosion
• Takeaway Points
Objectives

• Understand the input to methods and models for estimating erosion, and how it is obtained

• Be able to use this information as part of estimating the probability of erosion leading to failure under various potential failure modes

• (Estimating the probability of failure due to rock or soil erosion is covered in other chapters)
Key Concepts

• Many potential failure modes require erosion of rock or soil to result in dam breach, such as:
  • Overtopping erosion of an embankment
  • Overtopping erosion of a concrete dam abutment or foundation
  • Erosion of an unlined spillway or river channel
  • Erosion of an unlined plunge pool (leading structural undermining)
  • Erosion of the spillway foundation where floor slabs have been damaged or lost

• Initiation of erosion does not equate to failure

• Judgement must be made concerning the progression of erosion over time (rate of erosion, duration of loading, progressive failure, etc.)

• It is important to consider erosion extent as well as the erosion potential
Erosion Process
How Erosion Starts

• Erosion can occur under high velocity flows which cause high soil/rock detachment/plucking rates

• A discontinuity exists which allows flow to concentrate, or changes the flow regime from sheet to turbulent

• Possible sources of discontinuities are:
  • Slope changes in downstream slope (flat slope changes to steep slope)
  • Obstacles such as trees, vegetation, guard rails, etc.
  • Bare spots in grass cover
  • Groins or abutments
  • Change in cover materials
  • Open pipes or channels through the soil
Headcut Erosion Process

1. Flaw Exists in Protective Cover
2. Flow Concentrates and Surface Erosion Initiates at Flaw
3. Headcut Forms and Advances Upstream
4. Breach forms, if erosion and duration sufficient
5. (Note: if slope is composed of cohesionless soil, downward erosion may occur without a headcut forming first.) – but erosion mechanisms are more complicated.
Erosion Mechanisms
Erosion/Scour Mechanisms (Plunging Jet)

- Turbulence Production
  - Impinging Jet
  - Submerged Jet
  - Back Roller
  - Hydraulic Jump
  - Boundary Eddy Formation

- Particle Detachment (Cohesive Material)
  - Brittle Failure
  - Fatigue Failure
  - Block Removal (Ejection or Peeling)
  - Abrasion
  - Tensile Block Failure

- Particle Breakup/Transport
  - Armoring
  - Breakup
  - Transport
Erosion Process (Back Roller/Headcutting)
Particle Detachment - Cohesionless Materials

Flowing water induces a shear stress that progressively erodes the downstream embankment surface.

Constant overtopping (shown) or wave overwash initiates.
Armoring
Rock Erosion
Rock Erosion

- A few methods for estimating rock erosion exist:
  - Semi-empirical method developed by Annandale based on evaluating erosion resistance using a geotechnical erodibility index and erosion capacity based on stream power, calibrated to case studies.
  - Physics based method developed by Bollaert which comprehensively evaluates fracture propagation as well as block movement, but currently assumes all rock blocks are cubic or rectangular in shape and lifting mode only.
  - Block theory method developed by George which looks at the orientation and shape of the rock blocks, and flow velocities/pressures needed for their removal in a calculated failure mode, but currently is limited evaluating a few individual blocks.
  - The erodibility index method is currently used in the tools discussed in this course.
Erodibility Index (also defines the Headcut Erodibility Index)

- Based on 150 field and laboratory case studies
- All types of earth materials represented
- Primarily used for rock in current practice


\[ K_h = M_s \cdot K_b \cdot K_d \cdot J_s \]

- \( M_s \): mass strength number \( \rightarrow f(\text{Unconfined Compressive Strength, UCS}) \)
- \( K_b \): block size number \( \rightarrow f(\text{Rock Quality Designation, RQD & # of joint sets}) \)
- \( K_d \): joint shear strength number \( \rightarrow f(\text{joint roughness, alteration}) \)
- \( J_s \): joint orientation number \( \rightarrow f(\text{joint strike dip}) \)

Resistance to fracturing  Resistance to block removal
Stream Power

Stream power is calculated as a rate of energy dissipation for example using the following for flow down a uniform slope:

\[ P = \gamma UhS \]

- \( \gamma \) = unit weight of water
- \( U \) = flow velocity
- \( h \) = water depth
- \( S \) = hydraulic energy grade slope line

For a plunging jet (with no consideration for aeration, breakup, tailwater):

\[ P = \gamma qH/d \]

- \( \gamma \) = unit weight of water
- \( q \) = unit discharge
- \( H \) = fall height
- \( d \) = thickness of the jet as it impacts foundation material

For a back roller (no consideration for back eddies):

\[ P = \gamma q_3(v_m^2/2g) \]

- \( \gamma \) = unit weight of water
- \( q_3 \) = unit flow rate in upstream direction
- \( v_m \) = average water velocity in pool
- \( g \) = acceleration due to gravity
Erosion Potential
Stream Power and Headcut Erodibility Index, once determined, can be used to estimate the erosion potential.

![Diagram showing the relationship between Stream Power (P) and Headcut Erodibility Index (Kh). The diagram includes lines for different probability levels: P=0.99, P=0.50, and P=0.01. The data points are categorized into Scour and No Scour.]
Soil Erosion
Soil Erosion

Consider multiple variables:

• Flow Depth and Duration
• Shear Stress
• Flow Velocity
• Soil Material Type
• Geometry
• Armoring
• Vegetation
• Soil Properties (cohesion, particle size, density, water content etc.)
Hydraulic Shear Stress for Surface Flow

Shear stress is often used to determine if a material will erode. In a channel or down a slope it can be defined as:

\[ \tau_b = \gamma R_b S_e \]

\( \gamma = \text{unit weight of water} \)
\( R_b = \text{hydraulic radius of the bed} \)
\( S_e = \text{energy slope} \)
Hydraulic Shear Stress in Crack or Pipe

\[ \tau = \rho_w g \left( \frac{\Delta H}{L} \right) \frac{A}{P_w} \]

- \( \rho_w \) = density of water
- \( g \) = acceleration due to gravity
- \( \Delta H \) = head loss in pipe or crack (due to friction)
- \( L \) = length of crack or pipe base
- \( A \) = cross-sectional area of crack or pipe
- \( P_w \) = wetted perimeter of crack or pipe

Since \( \gamma_w = \rho_w g \) and \( i = \frac{\Delta H}{L} \), then \( \tau = \gamma_w \frac{i A}{P_w} \)

Correlations For Estimating Soil Erosion Rate Parameters

Note: dispersive soils are a special class that may be extremely erodible and not represented on this chart.
Erosion Laws

Volume Erosion: \( \varepsilon = k_d(\tau - \tau_c) \)
- \( \varepsilon \) = rate of volume of material removed per unit surface area per unit time (e.g., mm/hr)
- \( \tau \) = hydraulic shear stress
- \( \tau_c \) = critical shear stress
- \( k_d \) = erodibility coefficient (typically \( \text{cm}^3/(\text{Ns}) \) or \( \text{ft/hr}/\text{psf} \))

Mass Erosion: \( m = C_e(\tau - \tau_c) \)
- \( m \) = rate of mass removed per unit surface area per unit time (e.g., kg/s/m²)
- \( \tau \) = hydraulic shear stress
- \( \tau_c \) = critical shear stress
- \( C_e \) = coefficient of soil erosion (typically \( \text{s/m} \))
- \( C_e = k_d(\rho_d) \)

Source: Wahl et al. (2009)
Surface Protection (Turf) Overwash Erosion

• Currently no equations to predict failure, just some overwash flume tests on different types of grasses and soils documented in two Colorado State University reports:
  - “Wave Overtopping Simulator Testing of Proposed Levee Armoring Materials” for New Orleans District, December 2010 (Table 3.1)
  - “Full-Scale Wave Overwash Resiliency Testing of Dike and Embankment on Florida Sandy Soils” for Jacksonville District, May 2013 (Table 6.1)
• Found loss of surface protection was better predicted based on cumulative overwash volumes, not critical shear stress
• Critical overwash volumes are dependant on grass types, but more so on the soils the turf is anchored in
  - Critical overwash volume for fat clays ~ 150,000 ft³/ft of levee/dam crest
  - Critical overwash volume for silty sand ~ 7,000 to 13,000 ft³/ft (50% grass cover)
Soil Erodibility Tests
Erosion Tests – JET Test

- Water Surface
- Potential Core
- Diffused Jet
- Original Bed
- Scoured Bed
- Jet Centerline
- Stress Distribution

Formulas:
\[ \tau_1 = \tau_0 \left( \frac{J_p}{J_1} \right)^2 \quad \text{for} \quad J_1 \geq J_p \]

- Head
- Point gage to measure scour depth
- Jet tube
- Water supply
- Nozzle
- Soil sample in mould
- Submergence tank
- Mould
Schematic of Hole Erosion Test
Results for JET and HET from USBR

Wahl 2010
Test Comparisons

- The relative erosion rankings are similar between HET and JET.
- HET and JET produce significantly different erosion rates for a given shear stress, HET generally slower erosion.
- Difference is most pronounced in “clumpy” soils.
- HET appropriate for small opening such as concentrated leak internal erosion.
- JET appropriate for overtopping or channel flow erosion.
- JET works well with a broader range of soils.
- WinDAM is calibrated to JET tests.
Factors Affecting Erosion Resistance
Compaction Water Content

![Graph showing factors affecting erosion resistance](image)

### Atterberg Limits

<table>
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<tr>
<th>Soil Sample</th>
<th>USCS Classification</th>
<th>Liquid Limit (%)</th>
<th>Plasticity Index (%)</th>
<th>% Sand &gt; 0.074 mm</th>
<th>% Clay &lt; 0.002 mm</th>
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</table>
Factors Affecting Erosion Resistance

- SM – Silty Sand
- ML – Silt
- CL – Lean Clay
- CH – Fat Clay

Filled shape: Wet of Optimum
Empty shape: Dry of Optimum

More Erodible

Less Erodible

Graph showing the relationship between plastic index and erosion resistance. The graph includes data points and a trend line indicating a negative correlation between plastic index and erosion resistance.
Factors Affecting Erosion Resistance
Proportion of Erodible and Resistant Materials

- **Plan View**
  - “Shear” Flow
  - “Plunging” Flow

- **Section Views**
  - “Low to Medium” Average Erodibility
  - “High” Average Erodibility

- **Colors**
  - Very Erodible
  - Moderately Resistant
  - Very Resistant
Factors Affecting Erosion Resistance
Native Materials

• Maximum Past Stress and Consolidation
• Cementation
• Wet/Dry Cycling
• Confinement
• Water Content when eroded (material curing)
Modeling Erosion
SITES

• Developed by USDA from observed Performance of Spillways to simulate headcut erosion in earthen spillways.
• Sites is a 1-Dimensional computer program that evaluates the stability and integrity of unlined channels using the three phase headcut erosion process. (It does not model a breach)
• The model run terminates when the headcut advances to the reservoir pool.
• The model was developed with a focus on soils, but has been applied to rock channels.
• SITES does not calculate breaches as flow and erosion are not coupled in the model.
WinDAM C

- Developed by the USDA from research conducted at the Agricultural Research Service in Stillwater, Oklahoma
- Incorporate spillway erosion from SITES and includes algorithms for dam breach simulation (SIMBA)
- Will examine breaching due to overtopping of homogeneous embankments composed of cohesive materials (overtopping flow and erosion are coupled)
- Uses the same three phase erosion process, but adds in a fourth step which is breach development
- Will route flows through the reservoir (you supply an inflow hydrograph)
- Allows for variable dam crest elevations (camber)
- Allows flexible specification of the inflow hydrograph
- Detail provided in the model output is not as specific as that provided by SITES for spillway erosion
- Allows the user to enter multiple spillways
Modeling things to remember...

• All models are wrong in some context; models are merely an oversimplification of reality and should be treated as such.
• Geometry and flow are as important as erodibility and other factors. More than one alignment may be necessary.
• Input to the model will require data from a multi-disciplinary team.
• Want to run a full range of flows, duration is important.
• Kd and Kh can HEAVILY influence the output of these models.
• Confront that issue explicitly:

PERFORM SENSITIVITY ANALYSIS!
More modeling things to remember …

- SITES and WINDAM may use terms that are familiar, but have different meanings, so it is important to understand what the program is referring to.
- Just because the model indicates that there is a potential for failure, does not mean that the model fails and vice-versa
- SITES cannot account for flow concentrations, variations in geometry (bends, cross slopes, changes in widths), etc.
Takeaway Points

• Many potential failure modes feature progressive erosion of rock or soil leading to breach

• Initiation of erosion does not equate to failure/breach

• The resistance of rock to erosion is typically defined by the erodibility index (or headcut erodibility index) (Kh).

• The resistance of soil to erosion is typically defined by the detachment rate (Kd).

• Hydraulic studies are needed to determine the erosive capacity of the water impacting the rock or soil.

• Modeling will help estimate probabilities of erosion to breach