IV-1 Erosion of Rock and Soil

Best Practices in Dam and Levee Safety Risk Analysis

Modified 12 June 2015

RECLAMATION
Managing Water in the West

US Army Corps of Engineers
BUILDING STRONG®

Key Concepts

- Most potential failure modes require erosion of rock or soil to result in dam breach
  - Overtopping erosion of an embankment
  - Overtopping erosion of a concrete dam abutment or foundation
  - Erosion of an unlined tunnel or spillway
  - Erosion of a channel downstream of a stilling basin due to flow in excess of capacity
  - Erosion of the spillway foundation where floor slabs have been damaged or lost

Key Concepts Ctd…

- It is important to consider erosion extent at the same time one evaluates the erosion potential.

- Just because something erodes, does not mean that the system fails.

How Erosion Starts

- Flow occurs with high velocities or high soil detachment rates.
- A discontinuity exists which allows flow to concentrate, or changes flow regime from sheet to turbulent.
- Possible sources of discontinuities are:
  - Slope changes in downstream slope
  - Trees or vegetation
  - Bare spots in grass cover
  - Groins or abutments
  - Change in cover materials

Erosion Process

Erosion occurs in four distinct phases

1. Surface Erosion (Removal of Vegetal Cover)
2. Concentrated Flow Erosion (Headcut Formation)
3. Erosion Progression (Headcut Advance)
4. Breach Formation

Spillway Erosion Process

Flaw Exists in Vegetal Cover

1. Surface Erosion
2. Concentrated Flow at Discontinuities
3. Headcut Advance

Rock Erosion

- Many of the methods used currently to analyze rock were developed for mining applications, or used data from these methods.
  - Barton's Q-System characterized rock for tunneling.
  - Kirsten's ripability index established relationships between strength of rock and size of excavation equipment.
  - Annandale's erodibility index threshold line compares stream power against a headcut erodibility index.
  - Wibowo's uses logic regression to develop threshold probability lines that approximate the Annandale index.

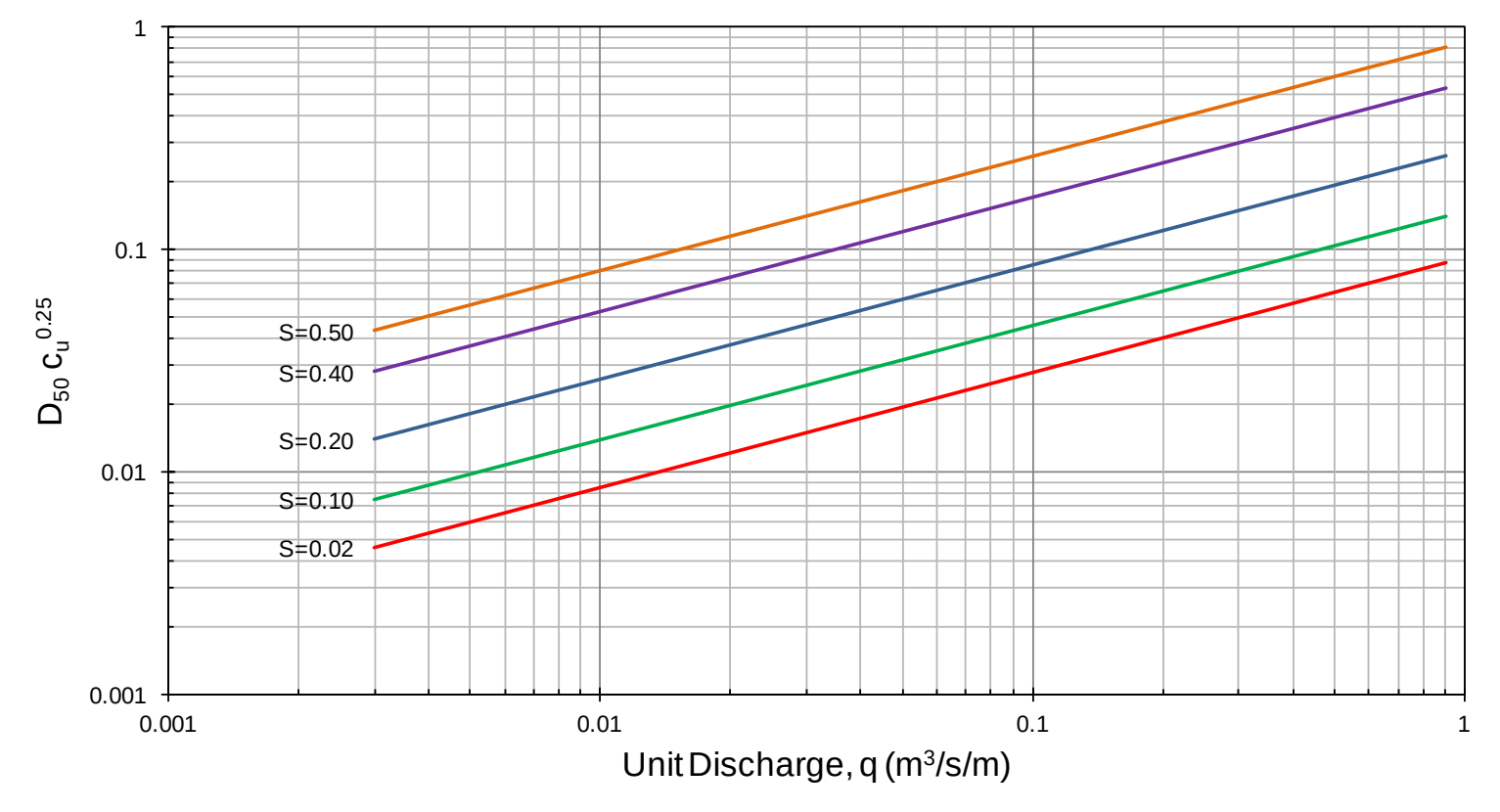
Soil Erosion

There are multiple variables to be considered when looking at erosion of soils:

- Flow Depth
- Shear Stress
- Flow Velocity
- Soil Material Type
- Geometry
- Armoring
- Vegetation
- Soil Properties (cohesion, particle size, etc…)

Rip-Rap/Rockfill Erosion Initiation Chart

(Frizzell *et al, 1998*)



Note that this chart comes from tests on material that was carefully placed, uniformly sized, and located in a straight sided flume. It is also important to know that a large portion of the flow occurred within the riprap itself.

Points plotting on the lines represent about 20 percent chance of erosion initiation.

Shear Stress

Shear stress is used to determine if a material will erode. It is defined as:

$$\tau_b = \gamma R_b S_e$$

γ = unit weight of water

R_b = hydraulic radius of the bed

S_e = energy slope

Stream Power

Stream power is calculated as a rate of energy dissipation using:

$$P = \gamma U h S$$

γ = unit weight of water

U = flow velocity

h = water depth

S = hydraulic energy grade slope line

Headcut Erodibility Index

- This is a value/calculation that is developed by relating the rock mass index developed by Barton/Kirsten to the power of flowing water.
- The headcut erodibility index was then correlated empirically to the erosive power of flowing water (stream power) and calibrated using performance data from lined and unlined spillways.
- The headcut erodibility index method can be used for either soil or rock.

Headcut Erodibility Index ctd…

The headcut erodibility index, K_h, is calculated using:

$$K_h = M_s K_b K_d J_s$$

M_s - Mass Strength

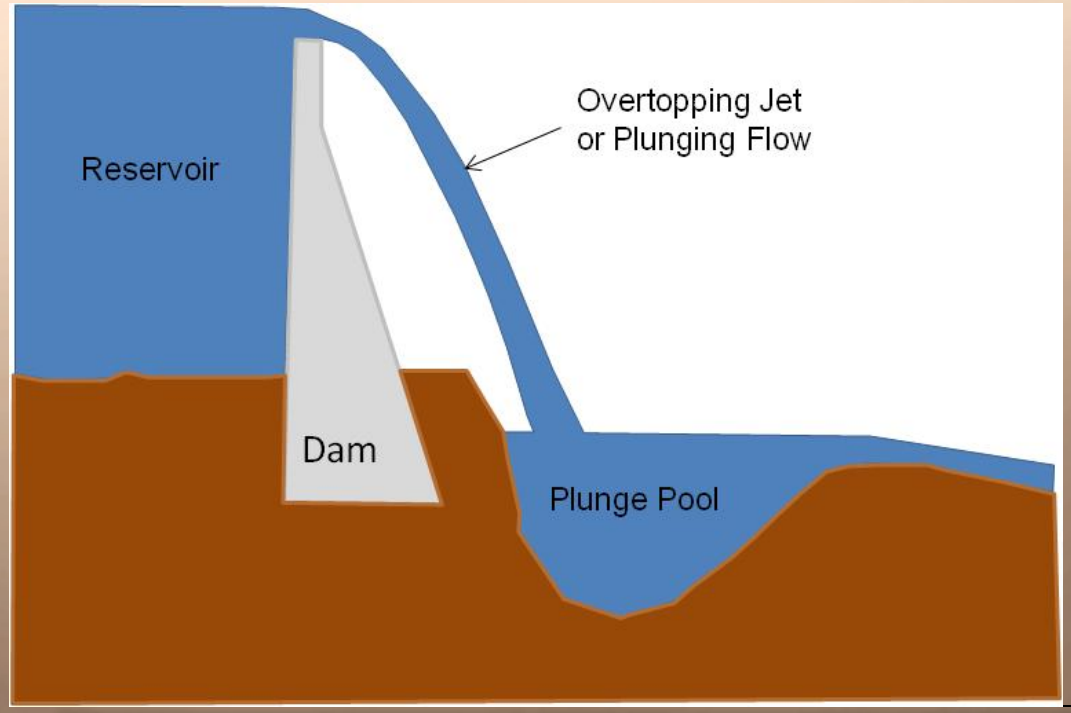
K_b - particle or fragment size of the rock blocks

K_d - Interblock Strength

J_s - Relative shape and orientation of blocks

Plunging Flow

Occurs where water flow transitions from flowing along a surface and can be directed downwards over a drop.



Plunging Flow Ctd…

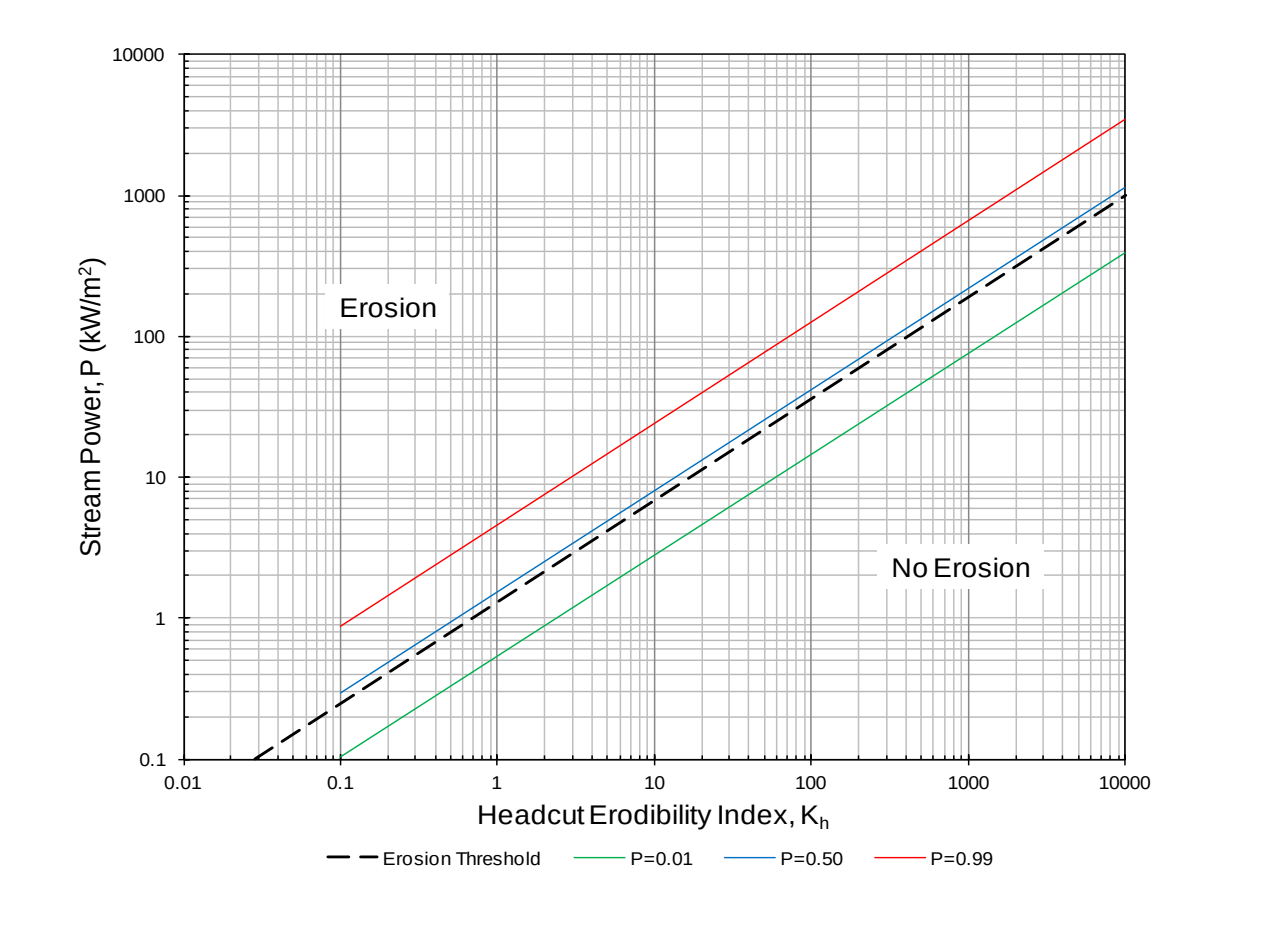
- There are multiple methods for estimating the plunge pool scour depth.
  - Veronese (1937) $Ys = 1.90H^{0.225}q^{0.54}$
  - Yildiz and Uzecek (1994) $Ys = 1.90H^{0.225}q^{0.54}\cos\alpha$
  - Mason and Arumugam (1985) $Ys=K(q^{x}H^{y}h^{w})/(g^{v}d^{z})$

- The plunge pool depth also has other factors that can alter the impacts of a plunging jet:
  - Air friction can degrade the jet, which would alter the impact point, and depth of the scour
  - Depth of the tailwater in relation to the height of the fall can alter the point of impact, and depth of the plunge.

For detailed definitions of the variables for these equations see chapter 15 of the Best Practices Manual.

Erosion Potential

Stream Power and Headcut Erodibility Index, once determined, can be used to estimate the erosion potential



Empirical Correlations For Estimating Soil Erosion Rate Parameters

$$\dot{\varepsilon} = k_d\,(\tau - \tau_c)$$

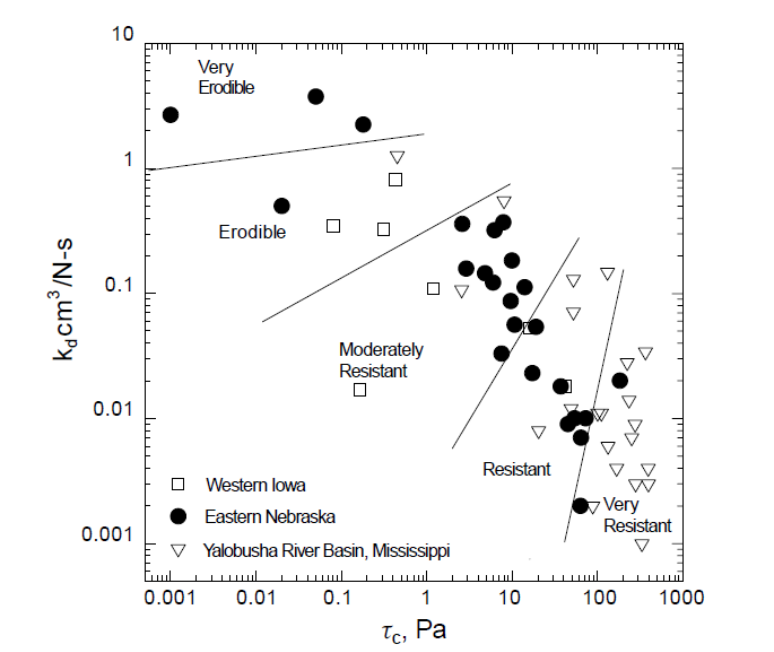
where

$\dot{\varepsilon}$ = the erosion rate,

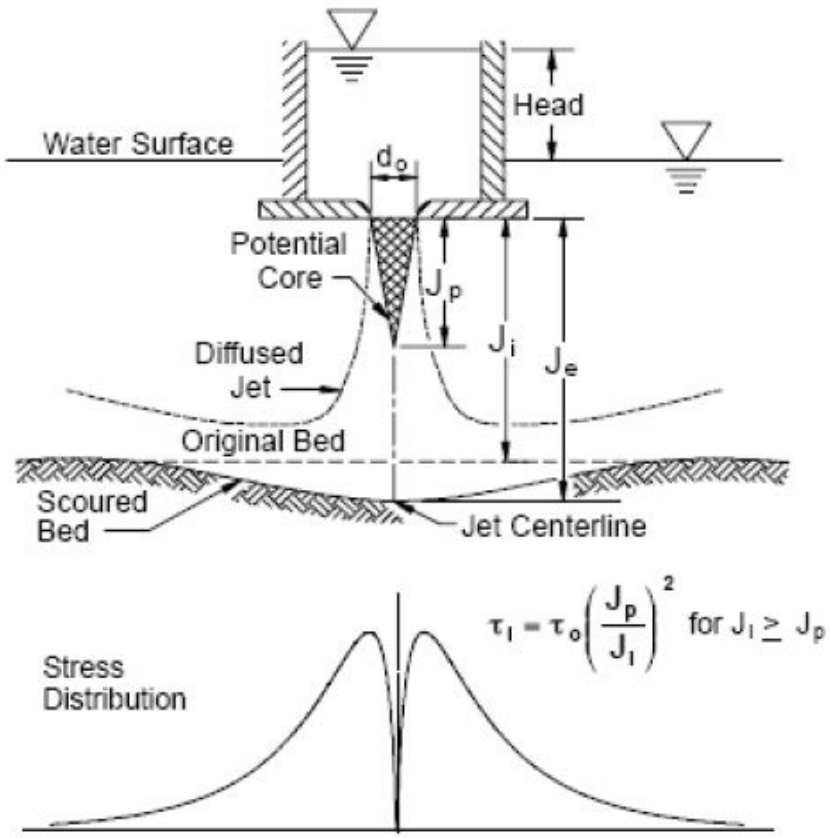
k_d = a detachment rate/erodibility coefficient (typically expressed in US units of ft^3/lb-hr),

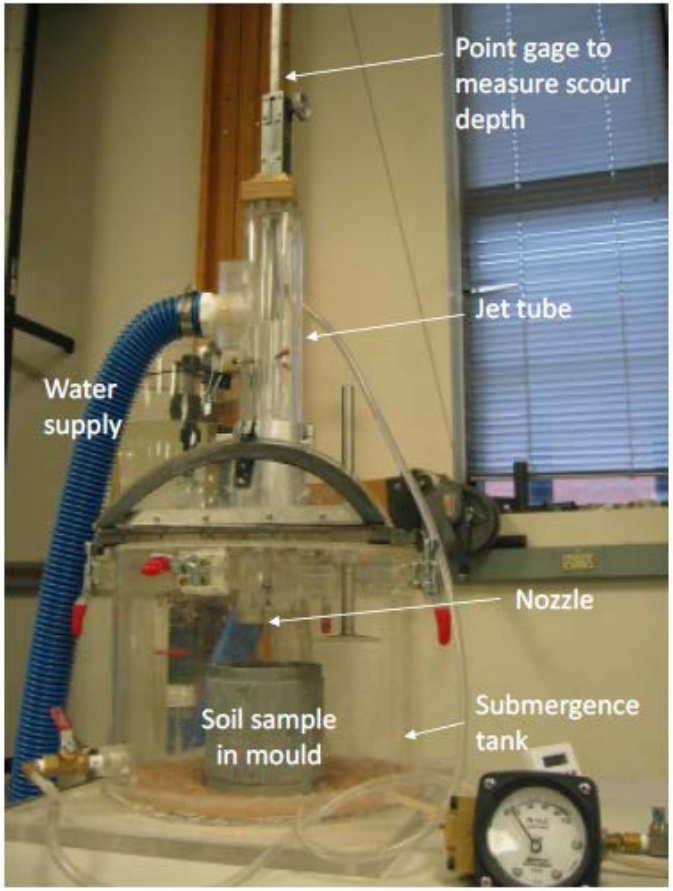
τ = the hydraulically applied boundary stress (typically in US units of lb/ft^2), and

τ_c = the critical stress required to initiate erosion (typically in US units of lb/ft^2).

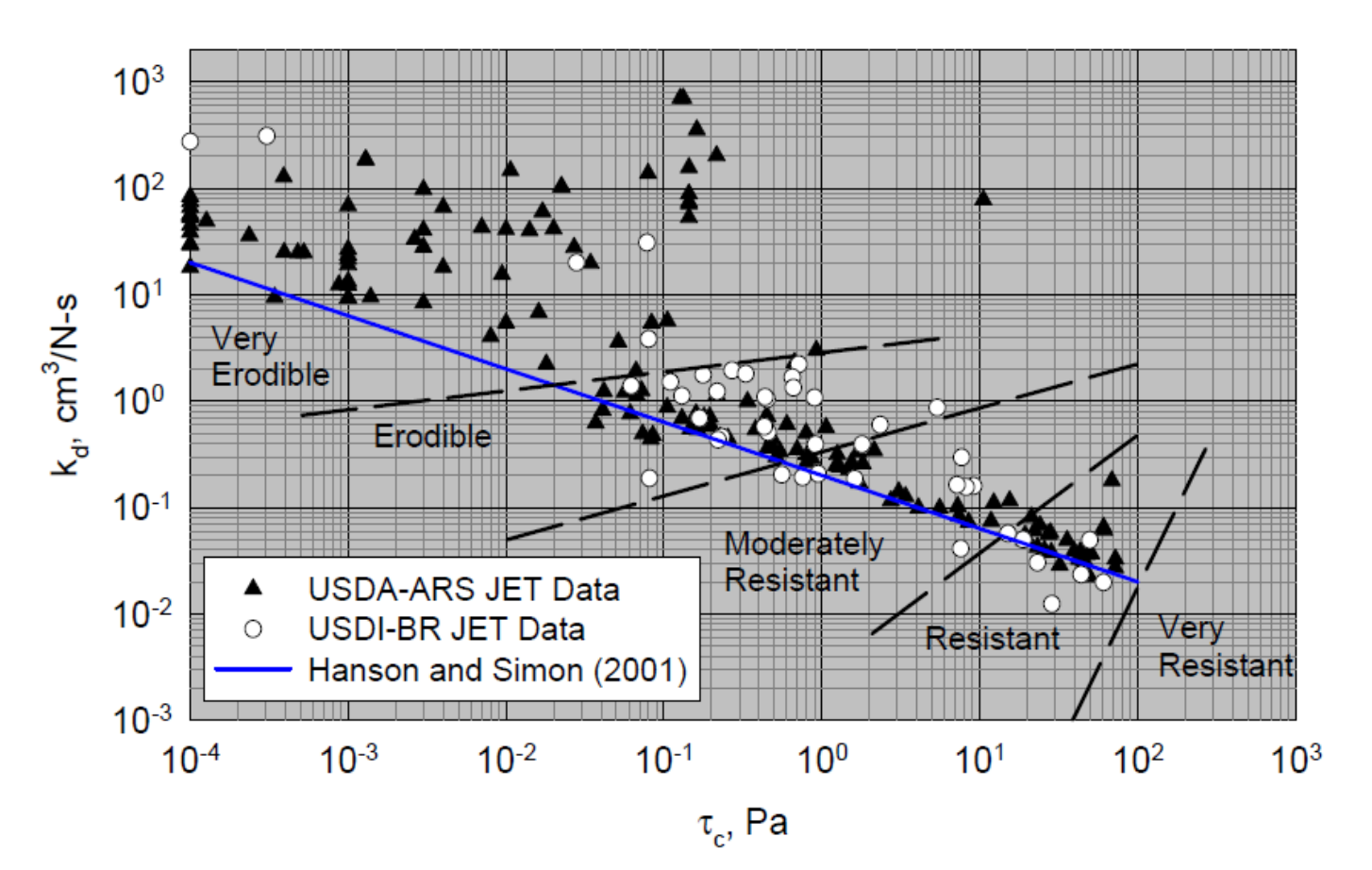


Erosion Tests – JET Test

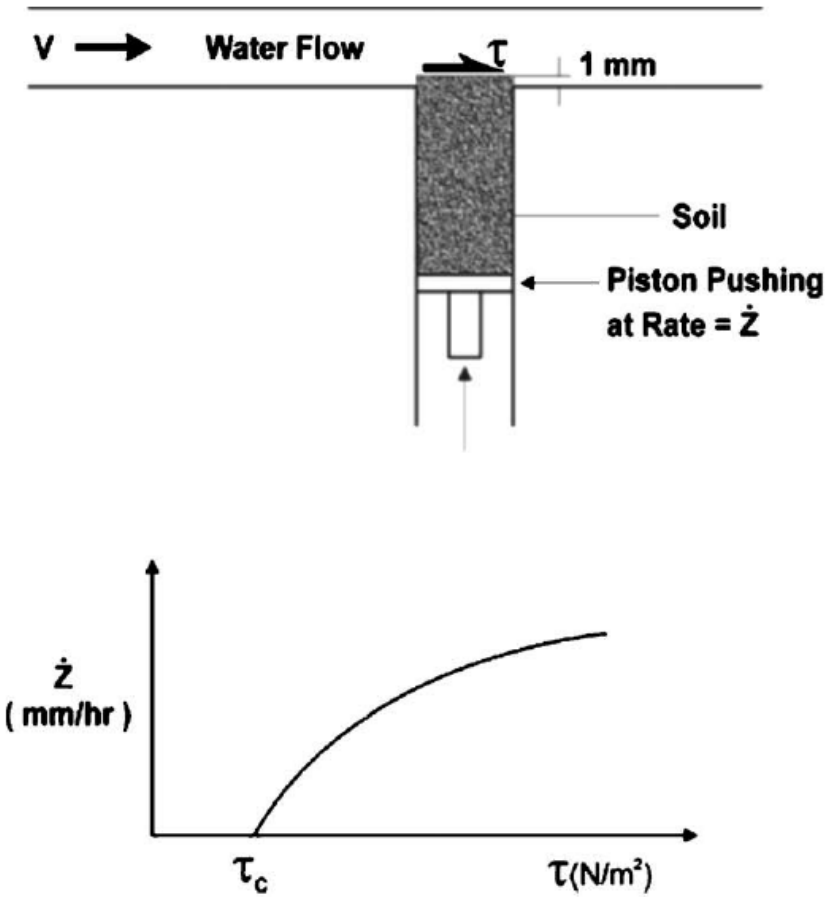


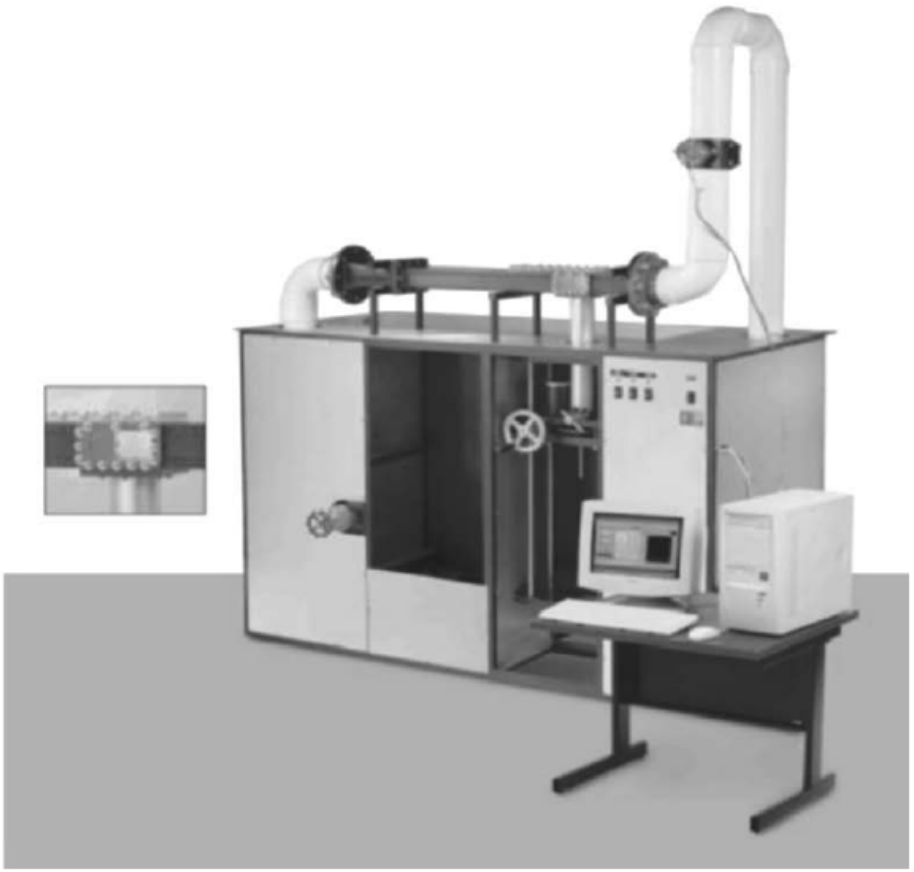


USDA and USBR Jet Test Results

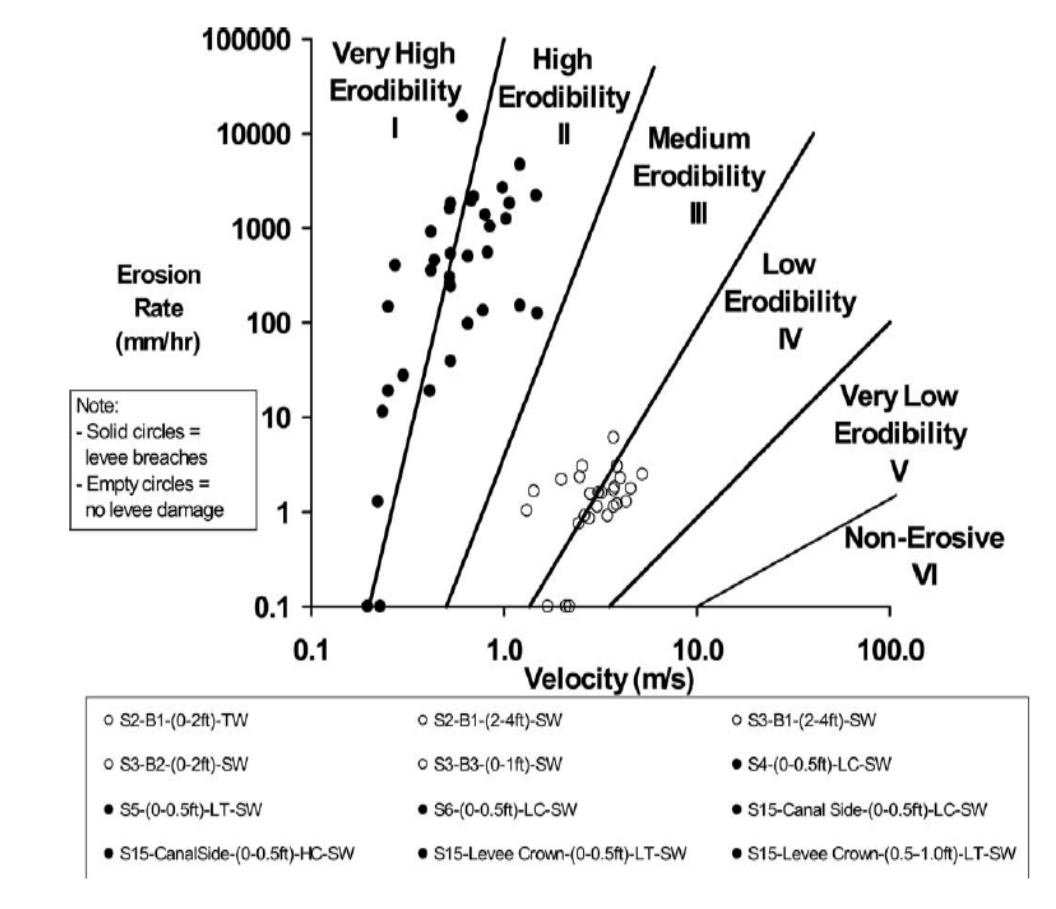


Erosion Tests – Erosion Function Apparatus

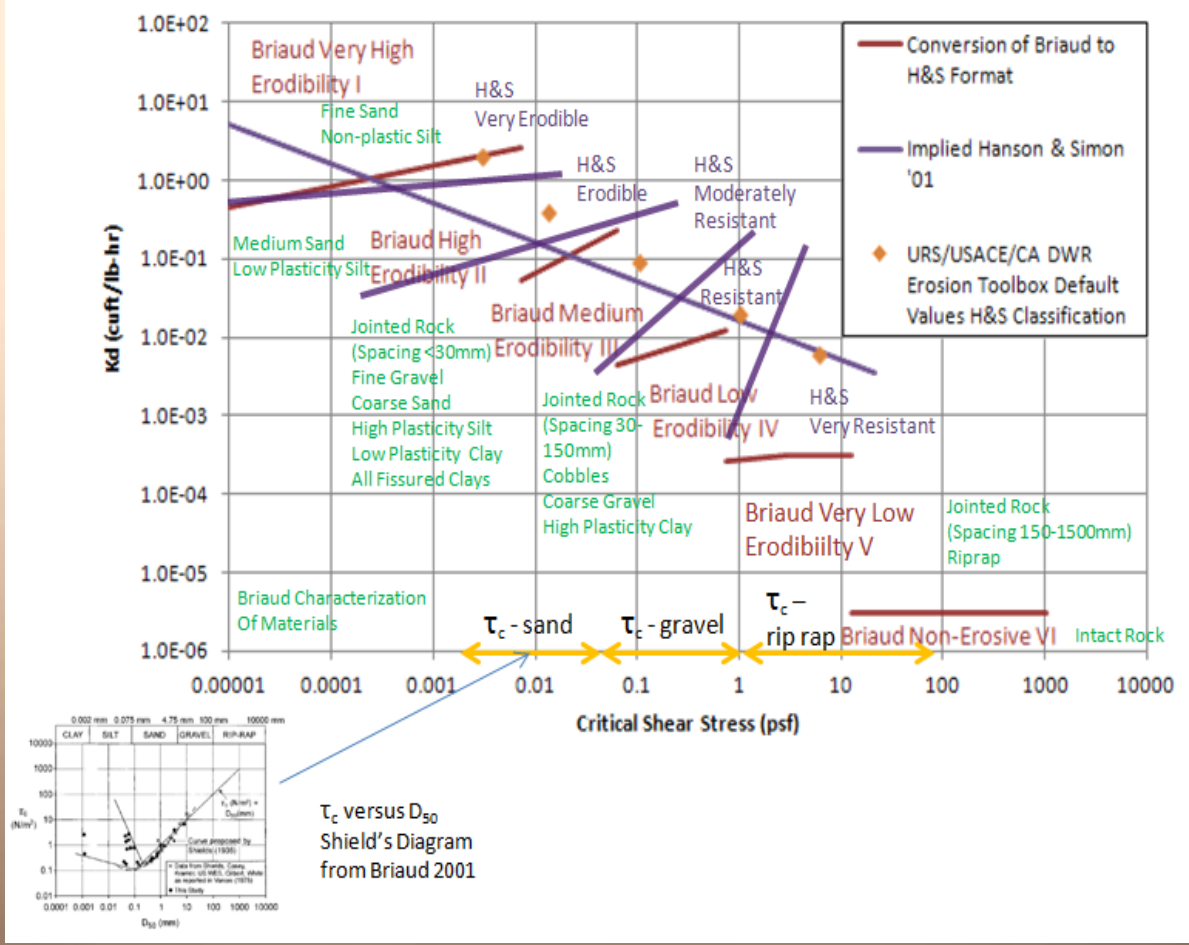




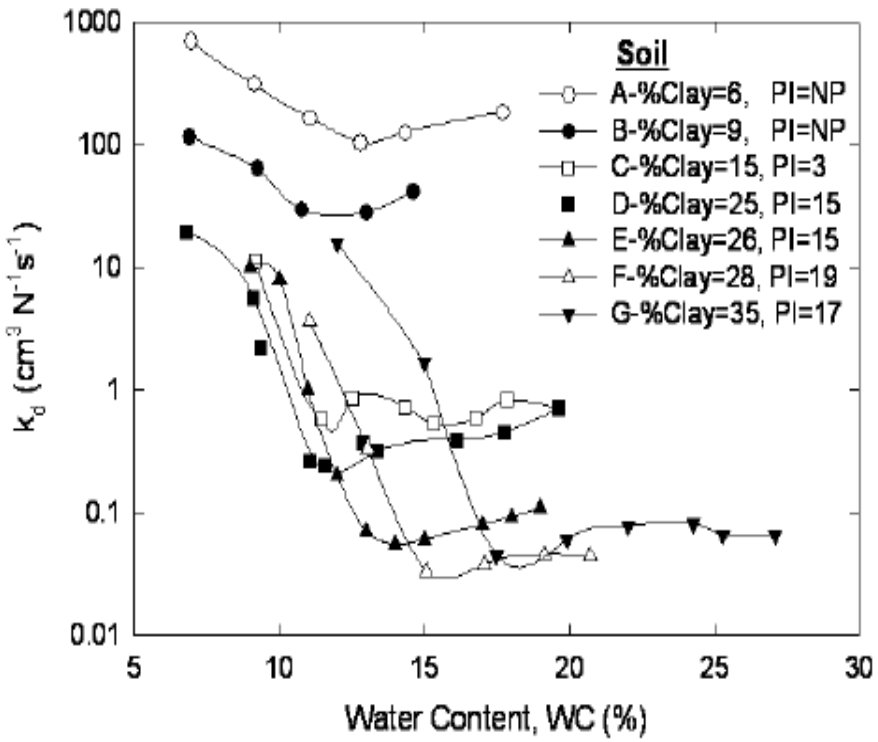
Briaud 2008 New Orleans Levee EFA Test Results



Comparison of Hanson and Simon and Briaud Erosion Resistance and Erodibility Classifications

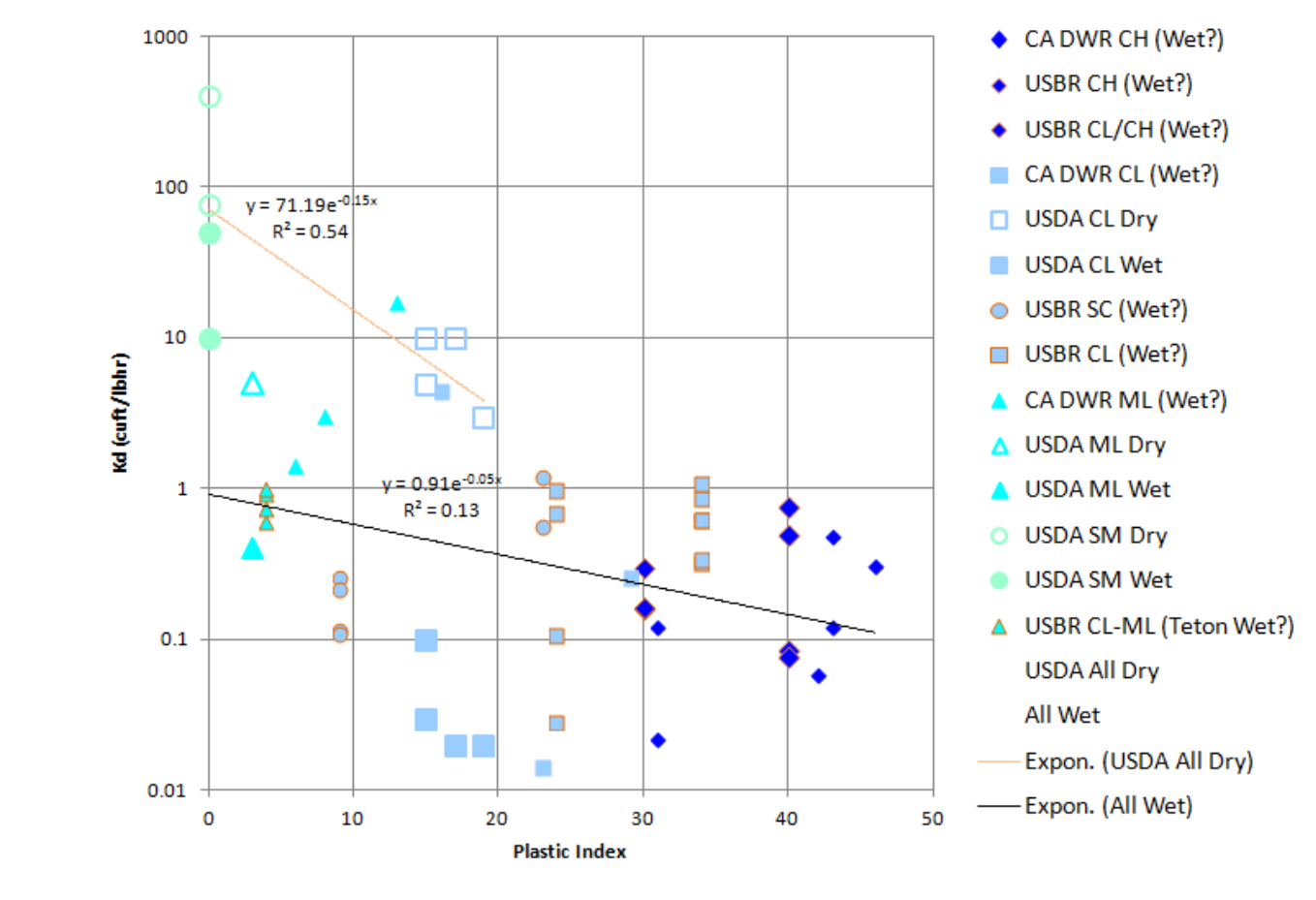


Factors Affecting Erosion Resistance Compaction Water Content



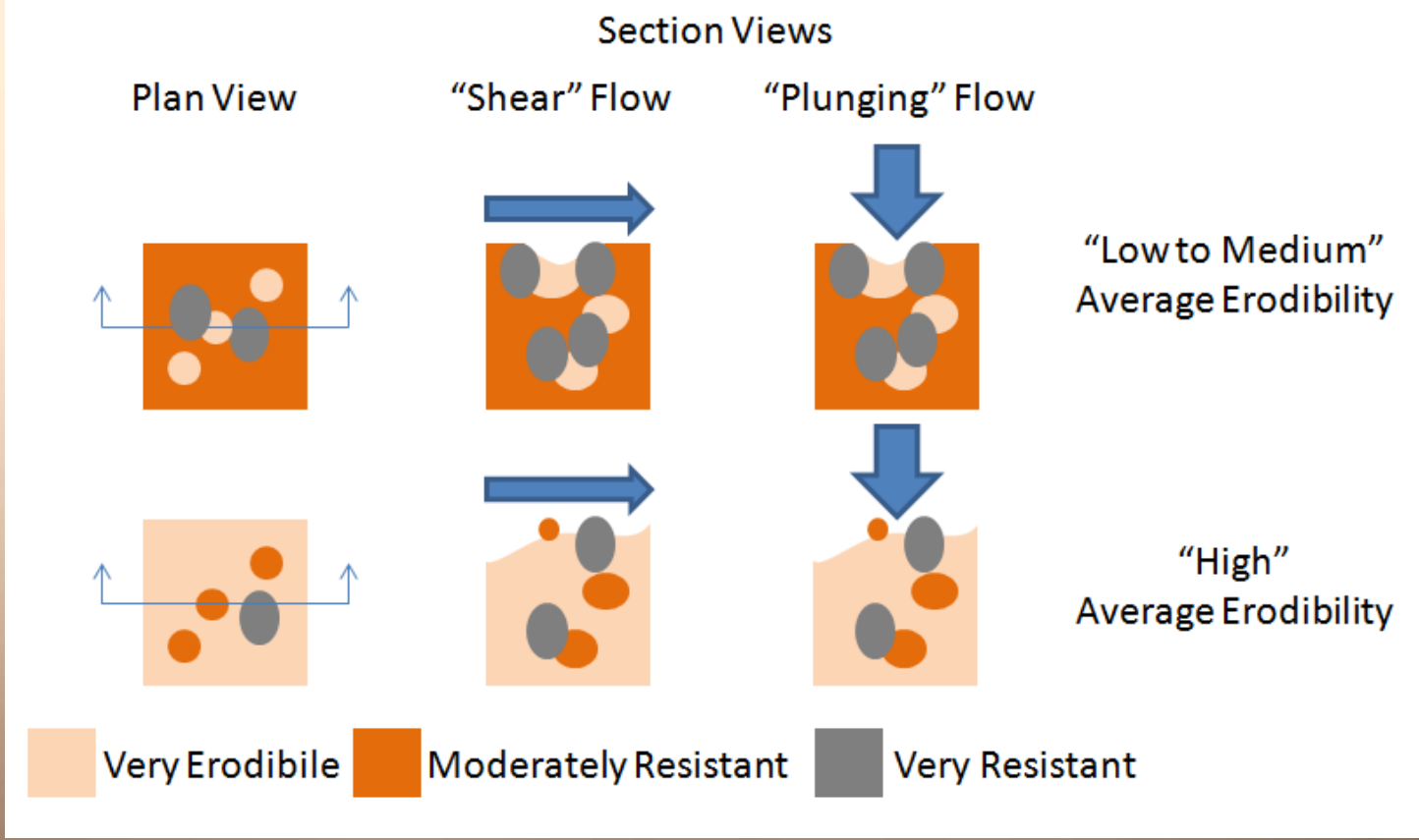
Soil Sample	USCS Classification	Atterberg Limits: Liquid Limit (%)	Atterberg Limits: Plasticity Index (%)	Texture: % Sand > 0.074 mm	Texture: % Clay < 0.002 mm
A	SM	NP	NP	73	6
B	SM	NP	NP	64	9
C	ML	23	3	32	15
D	CL	26	15	35	25
E	CL	31	15	24	26
F	CL	37	19	20	28
G	CL	37	17	13	35

Factors Affecting Erosion Resistance Plasticity?



Factors Affecting Erosion Resistance

Proportion of Erodible and Resistant Materials



Factors Affecting Erosion Resistance

Native Materials

- Maximum Past Stress and Consolidation
- Cementation
- Wet/Dry Cycling
- Confinement
- Water Content when eroded (material curing)

Numerical Modeling Methods for Soil and Rock Erosion

SITES – Developed by USDA from observed Performance of Spillways to simulate headcut erosion in earthen spillways.

WINDAM B – 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.

SITES

- 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 B

- Incorporates the SITES Software for spillway erosion.
- Will examine homogeneous embankment breaching due to overtopping. For 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.
- 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…

- Geometry and flow are as important as erodibility and other factors. More than one alignment may be necessary.
- These are reliability models, if SITES or WinDAM B are run and they do not indicate failure, you can be fairly confident that the system will not fail (depending on accuracy of the inputs).
- Input to the model will require data from a multi-disciplinary team.
- Want to run a full range of flows, duration is important.

Modeling things to remember ctd…

- 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.
- Remember the models are conservative, just because the model indicates that there is a potential for failure, does not mean that the model fails.
- SITES cannot account for flow concentrations, variations in geometry (bends, cross slopes, changes in widths), etc.